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LAND-SURFACE SUBSIDENCE IN THE AREA OF MOSES LAKE NEAR TEXAS CI--ETC(U)
OCT 76 R K GABRYSCH, C W BONNET

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AD-A035 620

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GEOLOGICAL SURVEY, AUSTIN, TEXAS

OCTOBER 1976

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 76-32

Prepared in cooperation with the U.S. Army Corps of Engineers

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16. Abstracts Removal of water, oil, and gas from the subsurface in Harris and Galveston Counties has caused declines in fluid pressures, which in turn have resulted in subsidence of the land surface. Subsidence of the land surface at Moses Lake is due principally to the removal of ground water in adjacent areas. Significant subsidence of the land surface at Moses Lake began after 1900, and as much as 1.8 feet (0.55 m) of subsidence had occurred in the area by 1973.

Probable future subsidence was calculated by two methods for two loading situations. In the first loading situation, case I, the artesian head in the middle Chicot aquifer, in the Alta Loma Sand (Rose, 1943), and in the Evangeline aquifer would continue to decline at respective rates of 1, 3, and 3 feet (0.3, 0.9, and 0.9 m) per year until 1980 and then cease. In the second loading situation, case II, the artesian head in the middle Chicot aquifer, in the Alta Loma Sand, and in the Evangeline aquifer would continue to decline at respective rates of 1, 3, and 3 feet (0.3, 0.9, and 0.9 m) per year until 1990 and then cease.

17. Key Words and Document Analysis. 17a. Descriptors

*Subsidence, land-surface subsidence, artesian pressures, compaction, water-level declines

17b. Identifiers/Open-Ended Terms

Harris County, Texas; Galveston County, Texas

17c. COSATI Field/Group

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I

LAND-SURFACE SUBSIDENCE IN THE AREA OF MOSES LAKE NEAR TEXAS CITY, TEXAS

By R.K. Gabrysch and C.W. Bonnet

U.S. GEOLOGICAL SURVEY
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October 1976

UNITED STATES DEPARTMENT OF THE INTERIOR

Thomas S. Kleppe, Secretary

GEOLOGICAL SURVEY

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LAND-SURFACE SUBSIDENCE IN THE AREA
OF MOSES LAKE NEAR TEXAS CITY, TEXAS

By

R. K. Gabrysch and C. W. Bonnet

ABSTRACT

Removal of water, oil, and gas from the subsurface in Harris and Galveston Counties has caused declines in fluid pressures, which in turn have resulted in subsidence of the land surface. Subsidence of the land surface at Moses Lake is due principally to the removal of ground water.

There is no production of ground water at Moses Lake, but pumping in areas adjacent to Moses Lake, principally at Texas City, has caused artesian-head declines in the Chicot aquifer of as much as 150 feet (45.7 m). Significant subsidence of the land surface at Moses Lake began after 1900, and as much as 1.8 feet (0.55 m) of subsidence had occurred in the area by 1973.

The study of subsidence in the Moses Lake area included the collection of undisturbed clay samples from a test hole for laboratory analyses, collection of water-level records, and installation and monitoring of observation wells and a borehole extensometer.

Probable future subsidence was calculated by two methods for two loading situations. In the first loading situation, case I, the artesian head in the middle Chicot aquifer, in the Alta Loma Sand (Rose, 1943), and in the Evangeline aquifer would continue to decline at respective rates of 1, 3, and 3 feet (0.3, 0.9, and 0.9 m) per year until 1980 and then cease. In the second loading situation, case II, the artesian head in the middle Chicot aquifer, in the Alta Loma Sand, and in the Evangeline aquifer would continue to decline at respective rates of 1, 3, and 3 feet (0.3, 0.9, and 0.9 m) per year until 1990 and then cease.

Calculations employing the consolidation theory of soil mechanics did not result in satisfactory agreement between predicted and measured subsidence. Calculations using field records of subsidence and artesian-head decline indicated an ultimate subsidence of between 3.0 and 3.3 feet (0.9 and 1.0 m) under the conditions of case I and between 3.9 and 4.6 feet (1.2 and 1.4 m) under case II.

To halt subsidence in the near future, the artesian head must be increased, either by decreasing pumping or by repressurization by artificial recharge. Planned decreases in ground-water use in Galveston County and in the southern part of Harris County would probably increase artesian heads in the Chicot and Evangeline aquifers at Moses Lake by as much as 50 and 20 feet (15 and 6 m) respectively, by 1980.

INTRODUCTION

The pumping of vast quantities of ground water for municipal supply, industrial use, and irrigation in Harris and Galveston Counties has caused large declines in artesian heads, which in turn have caused subsidence of the land surface. One area where land-surface subsidence is critical is at Texas City in the eastern part of Galveston County. Near Texas City, the facilities of the U.S. Army Corps of Engineers, such as the gate and protective levees at the entrance of Moses Lake, could be affected by land-surface subsidence. The proximity to Texas City of the study area and test site at Moses Lake is shown on figure 1.

Noticeable land-surface subsidence resulting from the pumping of ground water first occurred in the Texas City area between 1938 and 1940 (American Oil Co., 1958). Before subsidence was definitely known, however, the search for an outside source of water had begun. After recognition of the subsidence problem, efforts were made to obtain water for industrial use from outside the area, and the delivery of surface water from the Brazos River began in 1948.

Objectives

At the request of the U.S. Army Corps of Engineers, the U.S. Geological Survey began an investigation in September 1972 of land-surface subsidence in the area of Moses Lake near Texas City. The objectives of this investigation are:

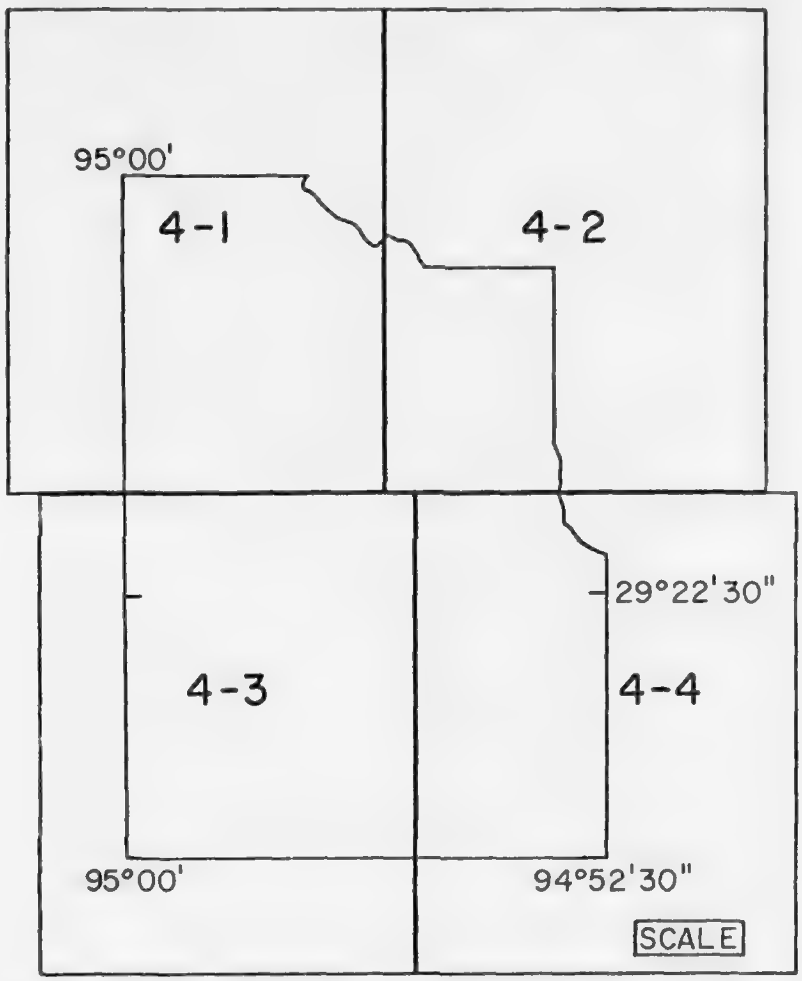
1. To determine the amount of subsidence due to the withdrawal of subsurface fluids.
2. To determine the rates of subsidence and the relation of subsidence to the decline in artesian head.
3. To predict the decline in artesian head during the next 50 years.
4. To predict the rate of subsidence caused by fluid withdrawal.
5. To predict the maximum subsidence to be expected during the next 50 years.

Metric Conversions

For those readers interested in using the metric system, metric equivalents of English units of measurements are given in parentheses. The English units used in this report may be converted to metric units by the following conversion factors:

FIGURE 1

LOCATION OF TEST WELLS AND THE TEST SITE IN THE MOSES LAKE STUDY AREA



Index map showing page numbers of each component of figure 1

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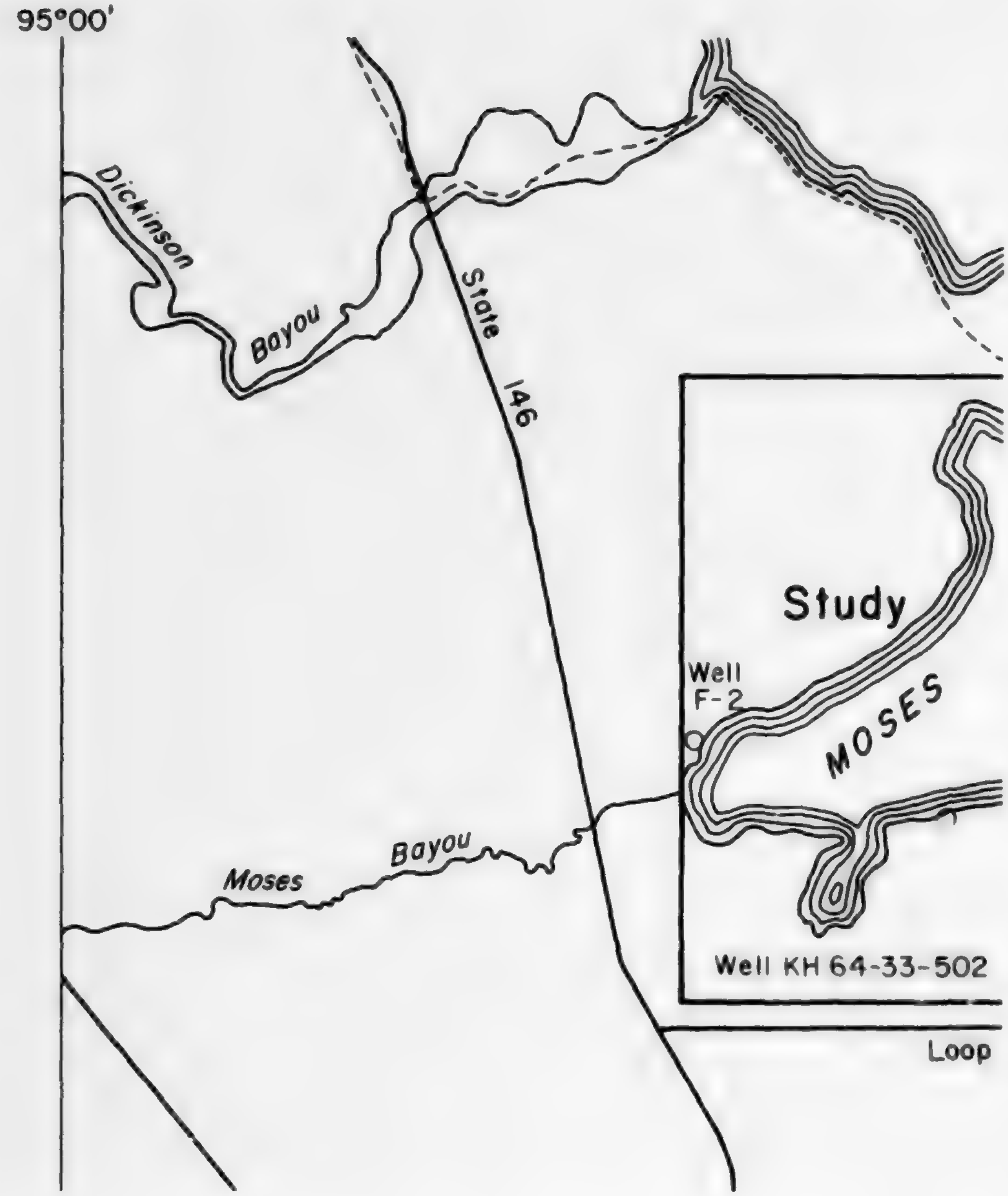

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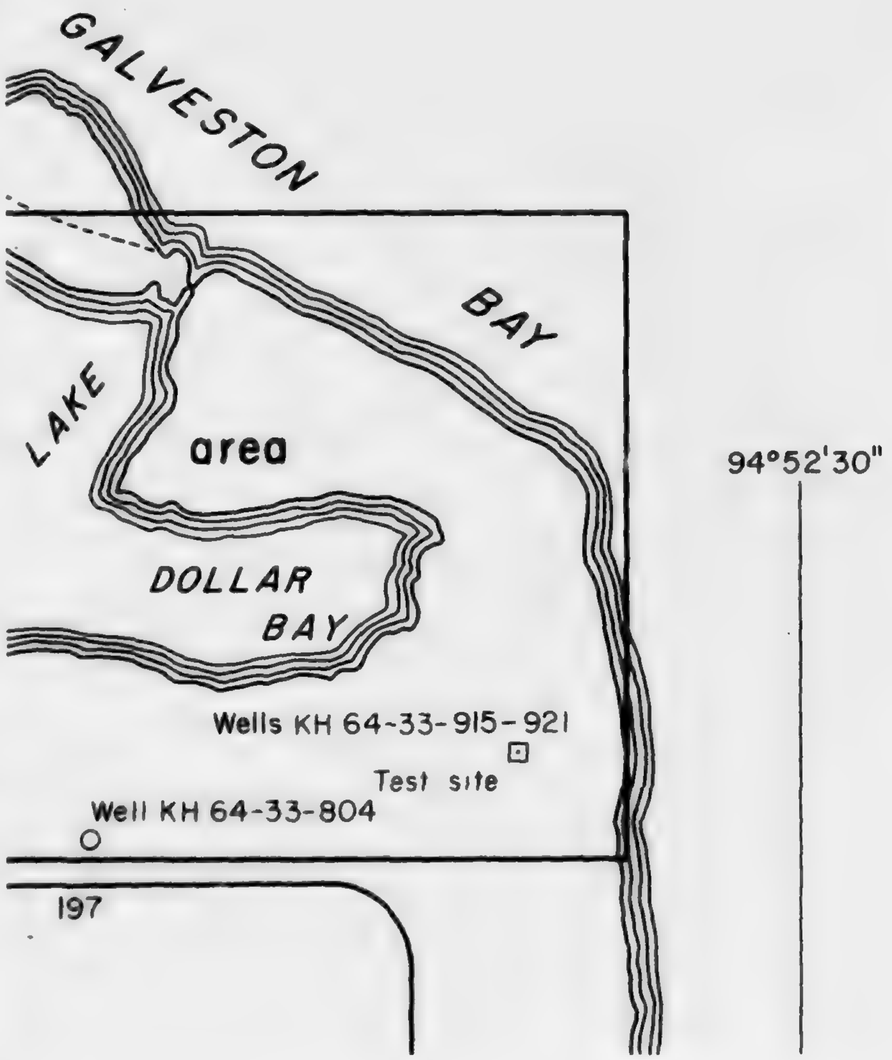
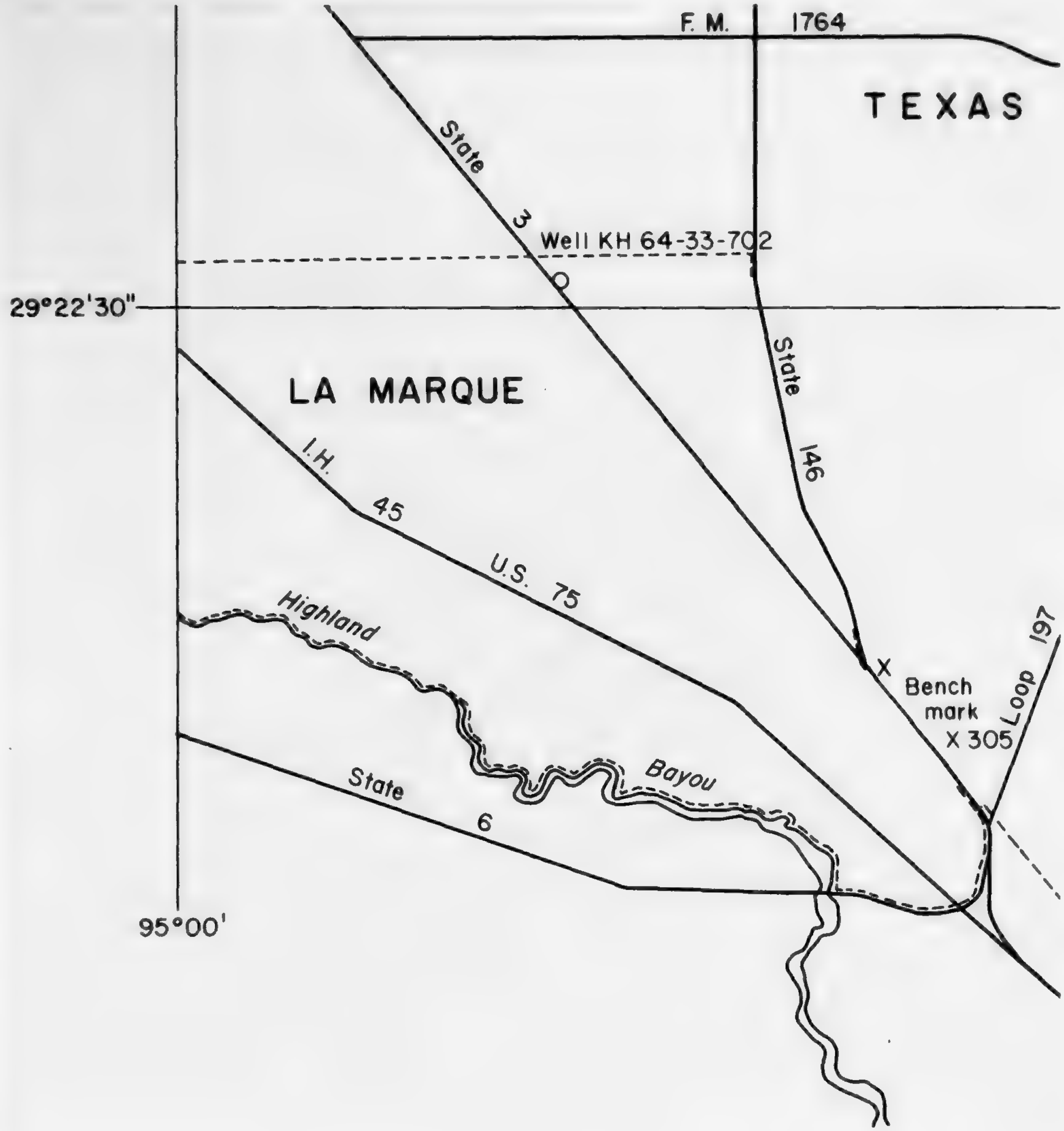
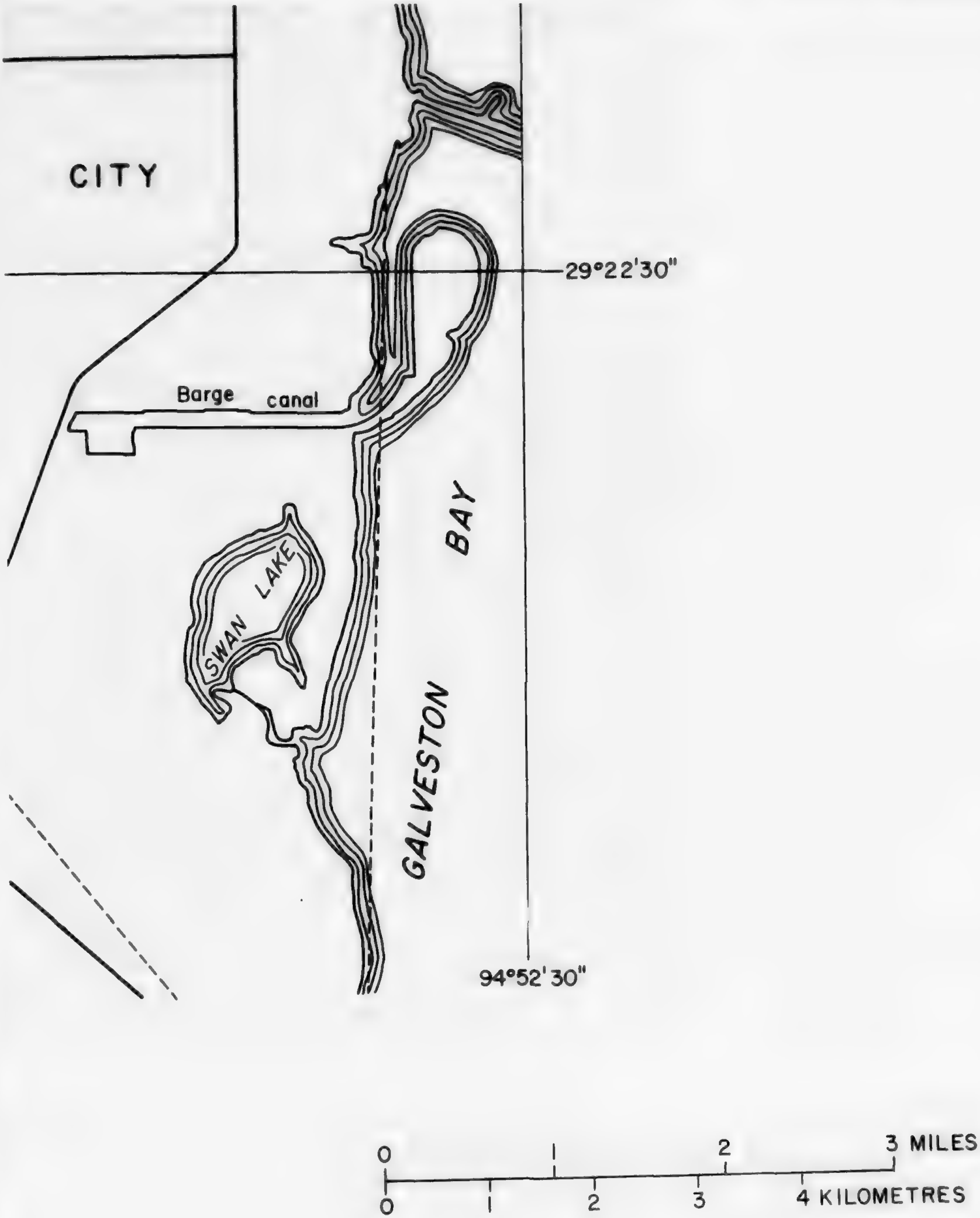




Base from U.S. Geological Survey
topographic quadrangles


CITY
29°22'30"
Barge canal
BAY
SWAN LAKE
GALVESTON
94°52'30"
0 1 2 3 MILES
0 1 2 3 4 KILOMETRES

From		Multiply by	To obtain	
Unit	Abbreviation		Unit	Abbreviation
feet	--	0.3048	metres	m
$feet^{-1}$	ft^{-1}	3.2808	$metres^{-1}$	m^{-1}
miles	--	1.609	kilometres	km
million gallons per day	million gal/d	0.04381	cubic metres per second	m^3/s
pounds per square inch	lb/in^2	0.07031	kilograms per square centimetre	kg/cm^2
tons per square foot	ton/ft^2	0.9765	kilograms per square centimetre	kg/cm^2

To convert centimetres per second (cm/s), as given in table 3, to inches per second (in/s), multiply by 0.3937.

To convert square centimetres per second (cm^2/s), as given in table 3, to square inches per second (in^2/s), multiply by 0.1550.

Acknowledgments

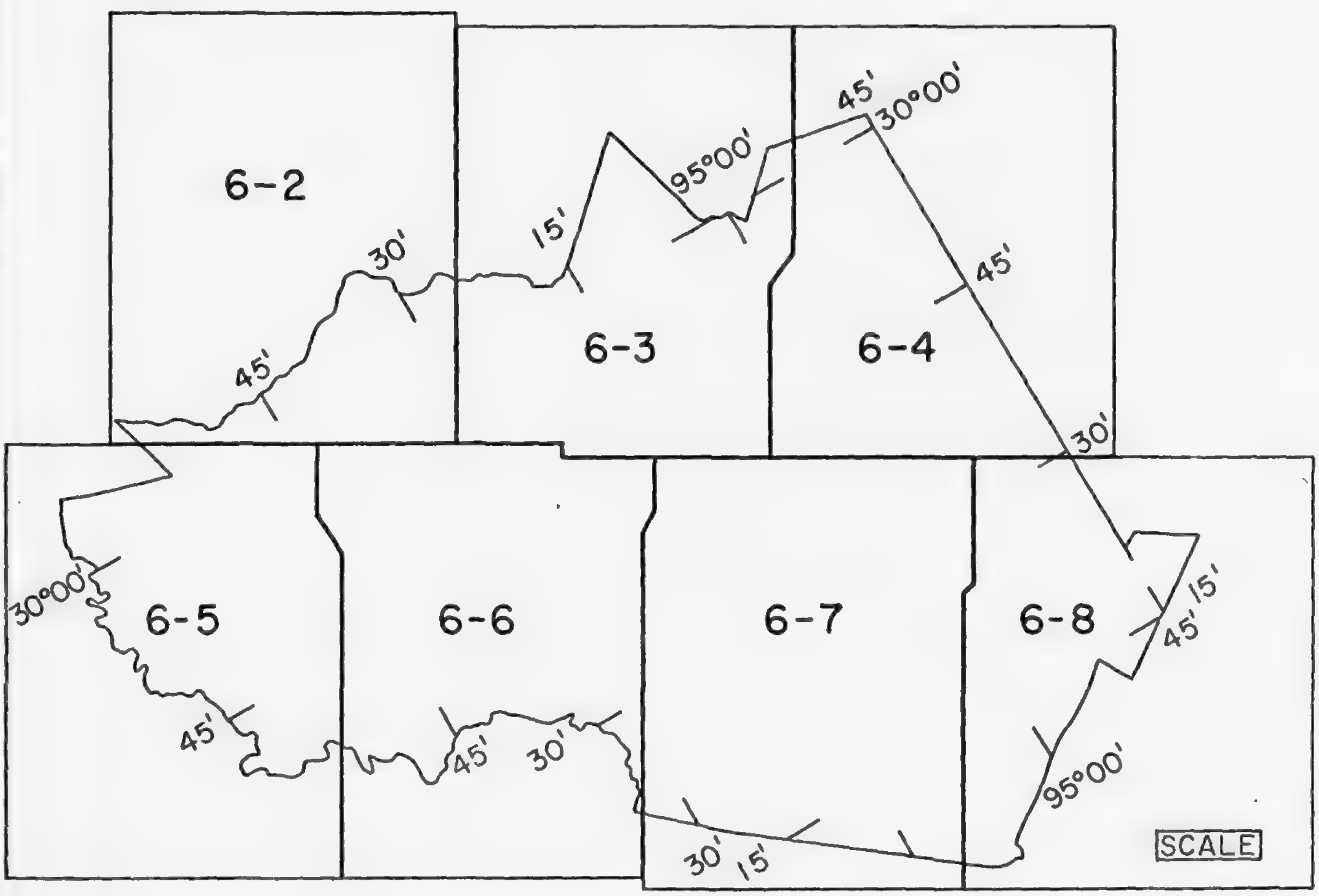
The authors gratefully acknowledge the assistance of Mr. Baker Birdwell, Birdwell's Water Well Service for his cooperation in drilling and sampling. The city of Texas City through Mr. Walter Gundermann, Director of Utilities, provided the site for installation of monitoring equipment.

CAUSES OF SUBSIDENCE

The primary cause of land-surface subsidence in the Moses Lake area is the decline in artesian head resulting from ground-water pumping. No significant pumping occurs in the study area; declines are due to pumping in adjacent areas, principally Texas City. Figure 2 shows the location of principal areas of ground-water pumping and the average rates of withdrawal in 1972.

FIGURE 2

PRINCIPAL AREAS OF GROUND-WATER PUMPING AND AVERAGE RATES OF WITHDRAWAL IN 1972



Index map showing page numbers
of each component of figure 2

EXPLANATION

14 Mgal/d	Heavily pumped area and 1972 ground-water pumpage (million gal/d = 0.04831 cubic metres per second)
A⊢—⊣A'	Location of generalized section (figures 3 and 4)

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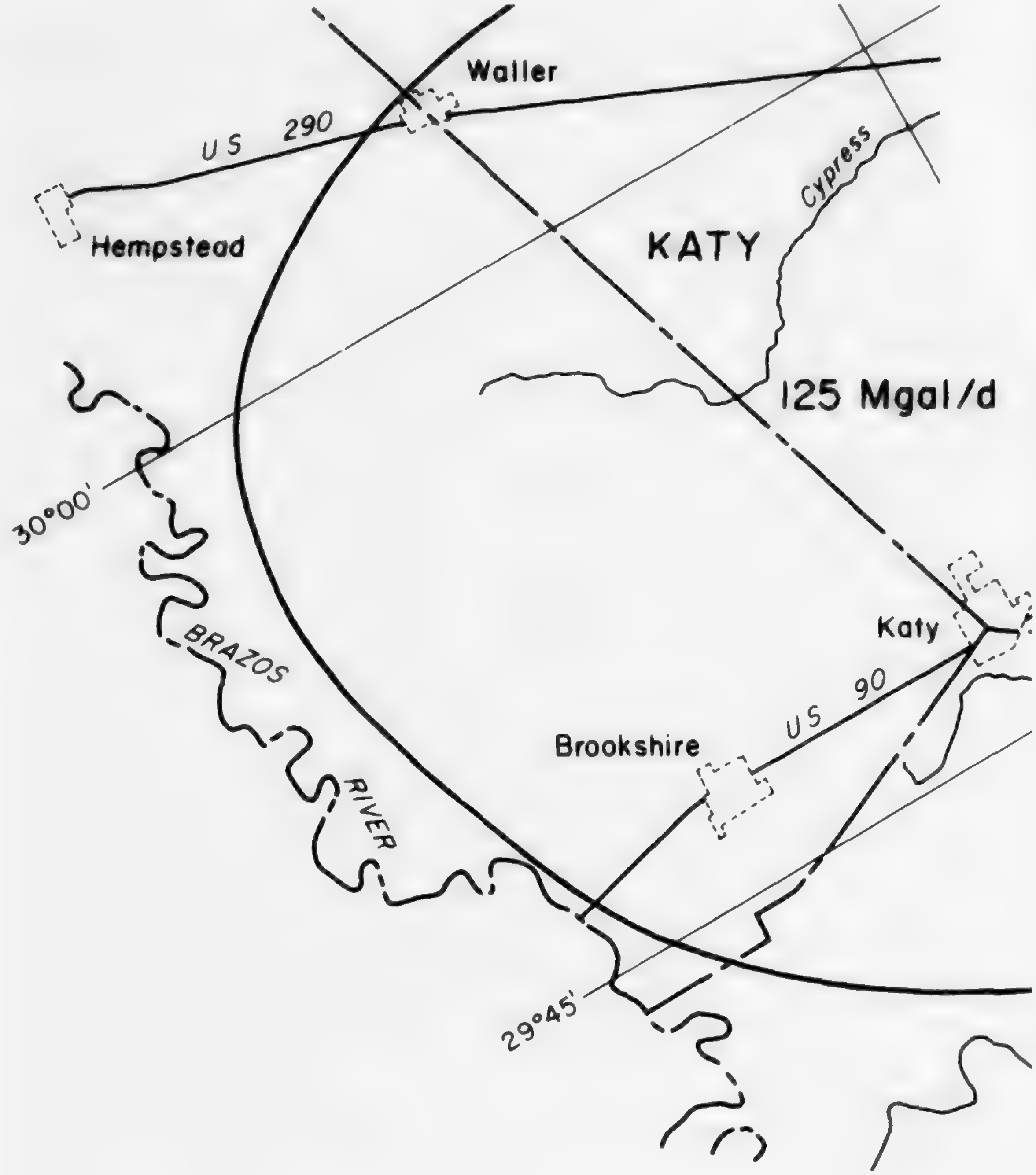
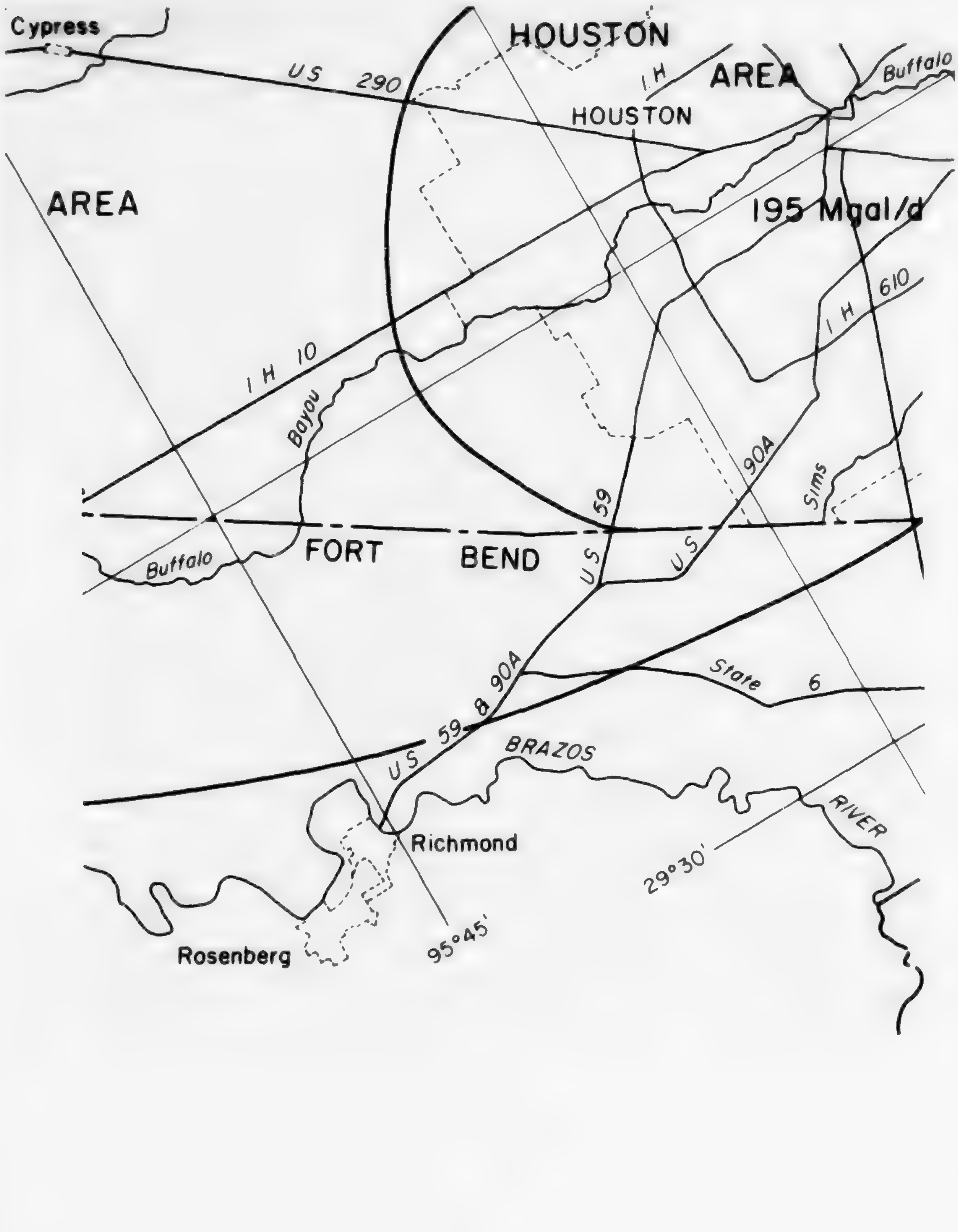
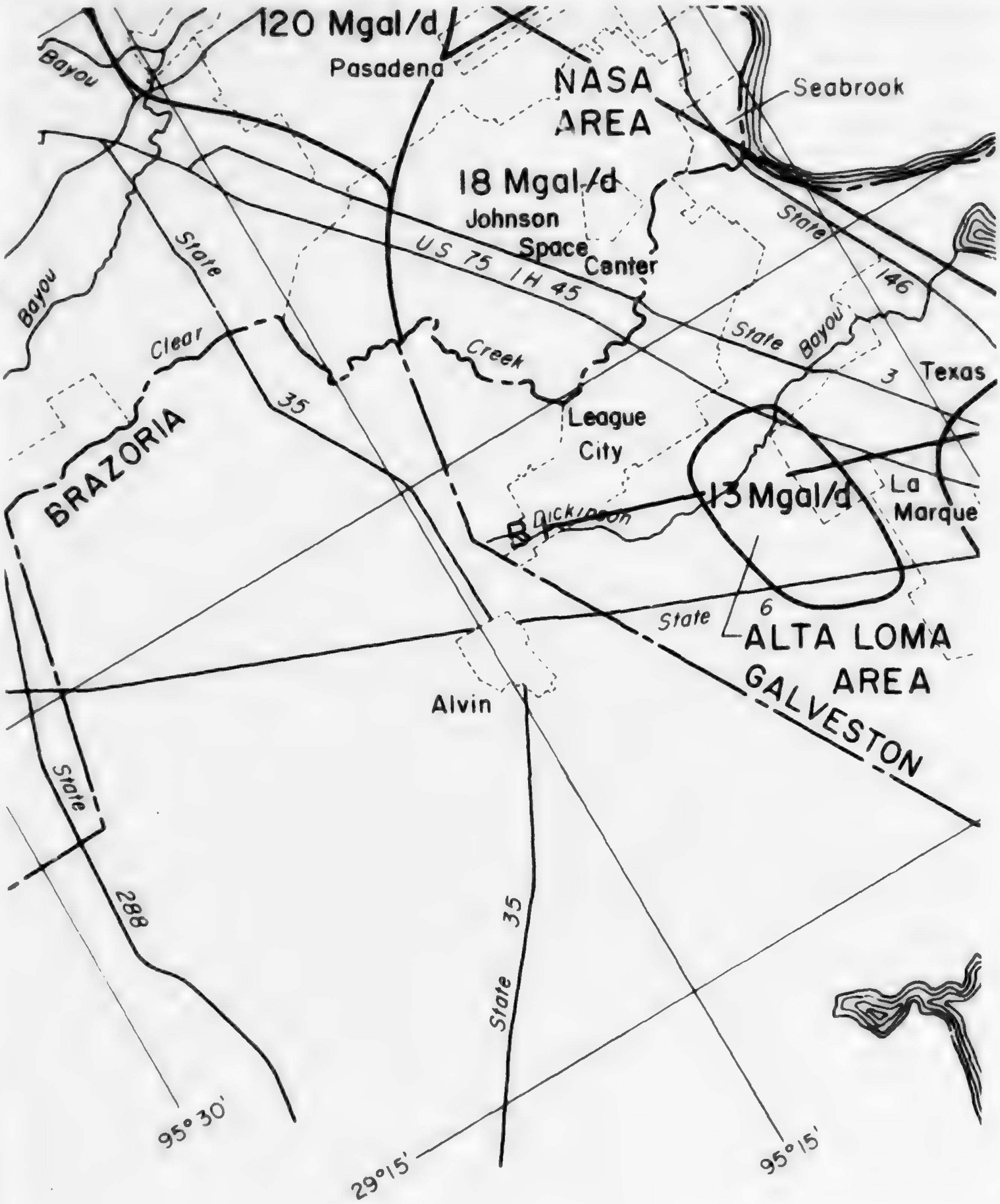
Liberty
94°45'
30°00'
TRINITY RIVER
LIBERTY
CHAMBERS
I H 10
29°45'
Bayou
Trinity Bay
BAYTOWN- LA
PORTE AREA
32 Mgal/d
Baytown
Crystal
Bay
GALVESTON
29°30'
La
Porte

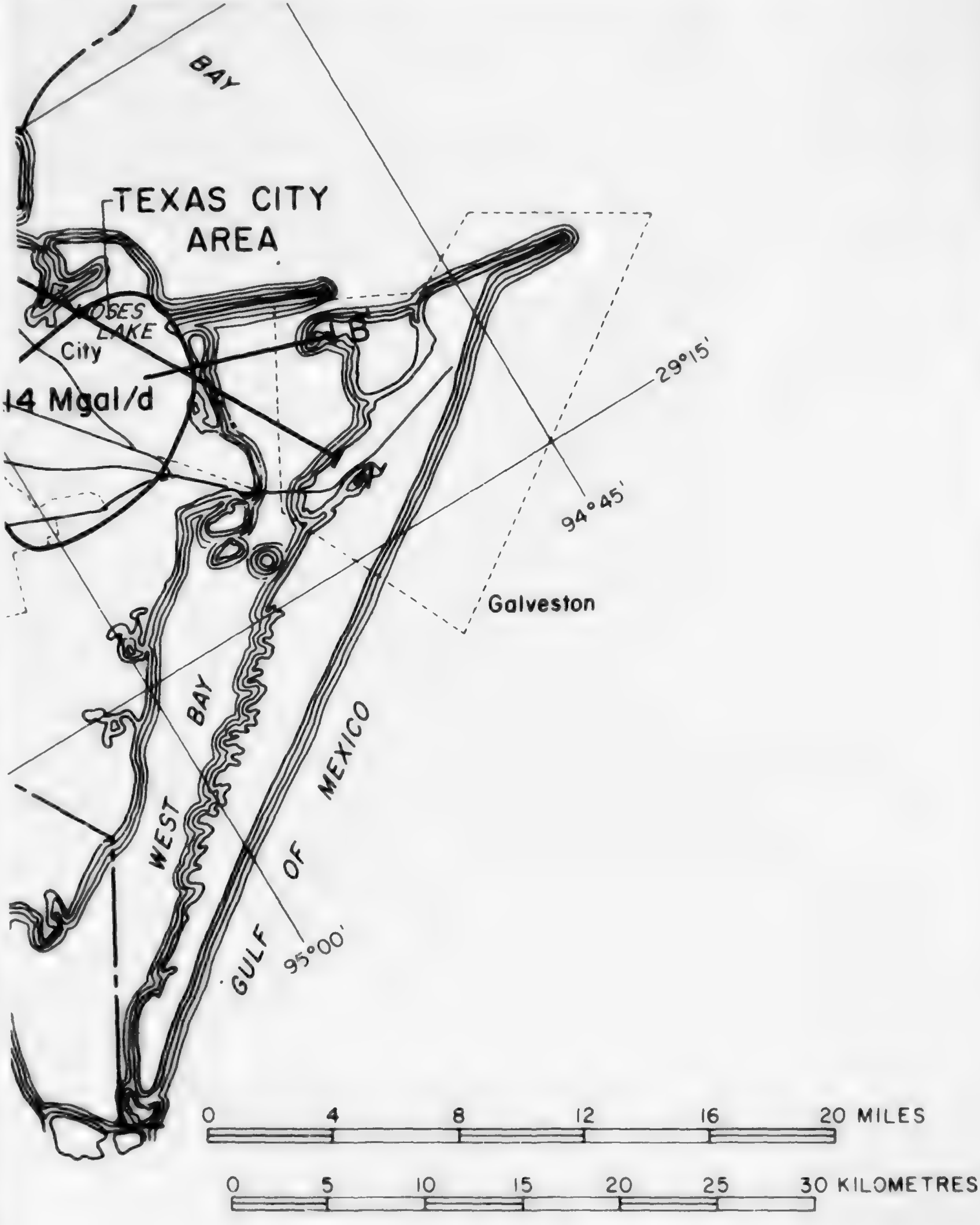


Base from Texas Highway Department
county highway maps



Cypress
HOUSTON
AREA
US 290
I H
HOUSTON
Buffalo
AREA
195 Mgal/d
I H 10
Bayou
I H 610
90A
Sims
59
Buffalo
FORT
BEND
U S
U S
State 6
90A
U S 59 & 90A
BRAZOS
RIVER
Richmond
29°30'
Rosenberg
95°45'


120 Mgal/d
Pasadena
NASA
AREA
Seabrook
18 Mgal/d
Johnson
Space
Center
US 75 IH 45
State
146
Bayou
Clear
Creek
State
35
BRAZORIA
League
City
State
3
Texas
13 Mgal/d
La
Marque
Dickinson
State
6
ALTA LOMA
AREA
GALVESTON
Alvin
State
288
State
35
95°30'
29°15'
95°15'



BAY
TEXAS CITY AREA
MOSES LAKE
City
14 Mgal/d
29°15'
94°45'
Galveston
WEST BAY
GULF OF MEXICO
95°00'
0 4 8 12 16 20 MILES
0 5 10 15 20 25 30 KILOMETRES

Ground-water pumping in the Texas City area increased from less than 2 million gal/d (0.09 m^3/s) in 1930 to about 12 million gal/d (0.5 m^3/s) in 1940, then increased to about 24 million gal/d (1.1 m^3/s) in 1944 and 1945. Withdrawals decreased slightly at the end of World War II, then decreased rapidly after 1948 when surface water from the Brazos River was brought into the area. Ground-water withdrawals averaged about 10 million gal/d (0.4 m^3/s) from 1950 to 1960, then gradually increased to 14 million gal/d (0.6 m^3/s) in 1972. About 53 percent of the water pumped in 1972 was for industrial use.

All of the ground-water withdrawals in the Texas City area are from sand or gravel beds within the Chicot aquifer system. Most of the withdrawals are from sand and gravel beds in the middle part of the Chicot aquifer, and the remainder is from the Alta Loma Sand of Rose (1943; hereafter referred to as the Alta Loma Sand), the basal sand of the Chicot aquifer. Declines in artesian head in the underlying Evangeline aquifer have resulted largely from pumping in Harris County and, before 1964, by upward leakage to the Alta Loma Sand, which had a lower head.

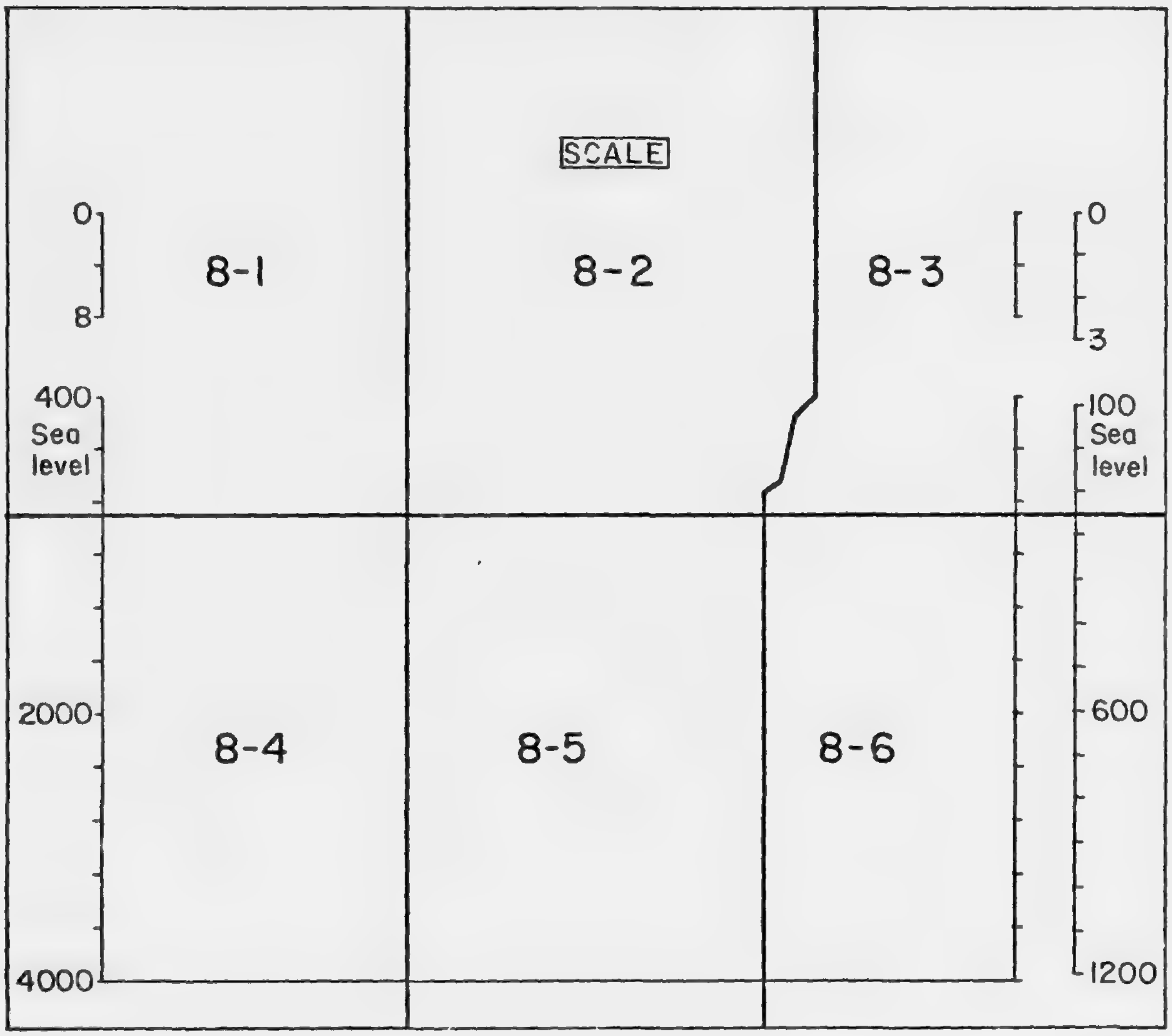
Figures 3 and 4 show the depths and thicknesses of the aquifers, the principal zones of ground-water withdrawal, the altitude of the potentiometric surfaces, and subsidence along lines from about 50 miles (80.5 km) northwest to about 8 miles (12.8 km) southeast of the study area (fig. 3), and from about 16 miles (25.7 km) west to about 6 miles (9.7 km) southeast of the study area (fig. 4). (Location of the profiles shown on fig. 2.)

SUBSIDENCE AT MOSES LAKE

Winslow and Doyel (1954) were the first to assemble data on subsidence in the Houston-Galveston region. Winslow and Wood (1959) added to the earlier findings when data became available. Gabrysch (1969) and Gabrysch and Bonnet (1974b) presented an analysis of subsidence in the region on the basis of the 1964 and 1973 releveling of bench marks by the National Geodetic Survey (formerly U.S. Coast and Geodetic Survey). The American Oil Company (1958) prepared a report describing subsidence at Texas City. These and all other available hydrologic and topographic data were used to prepare the maps of land-surface subsidence for 1943-73 and 1964-73 presented as figures 5 and 6.

FIGURE 3

HYDROLOGIC PROFILE A-A' FROM MONTGOMERY COUNTY TO TEXAS CITY SHOWING AQUIFERS, PRINCIPAL ZONES OF GROUND-WATER WITHDRAWAL, ALTITUDE OF THE POTENTIOMETRIC SURFACES, AND LAND-SURFACE SUBSIDENCE



Index diagram showing page numbers of each component of figure 3

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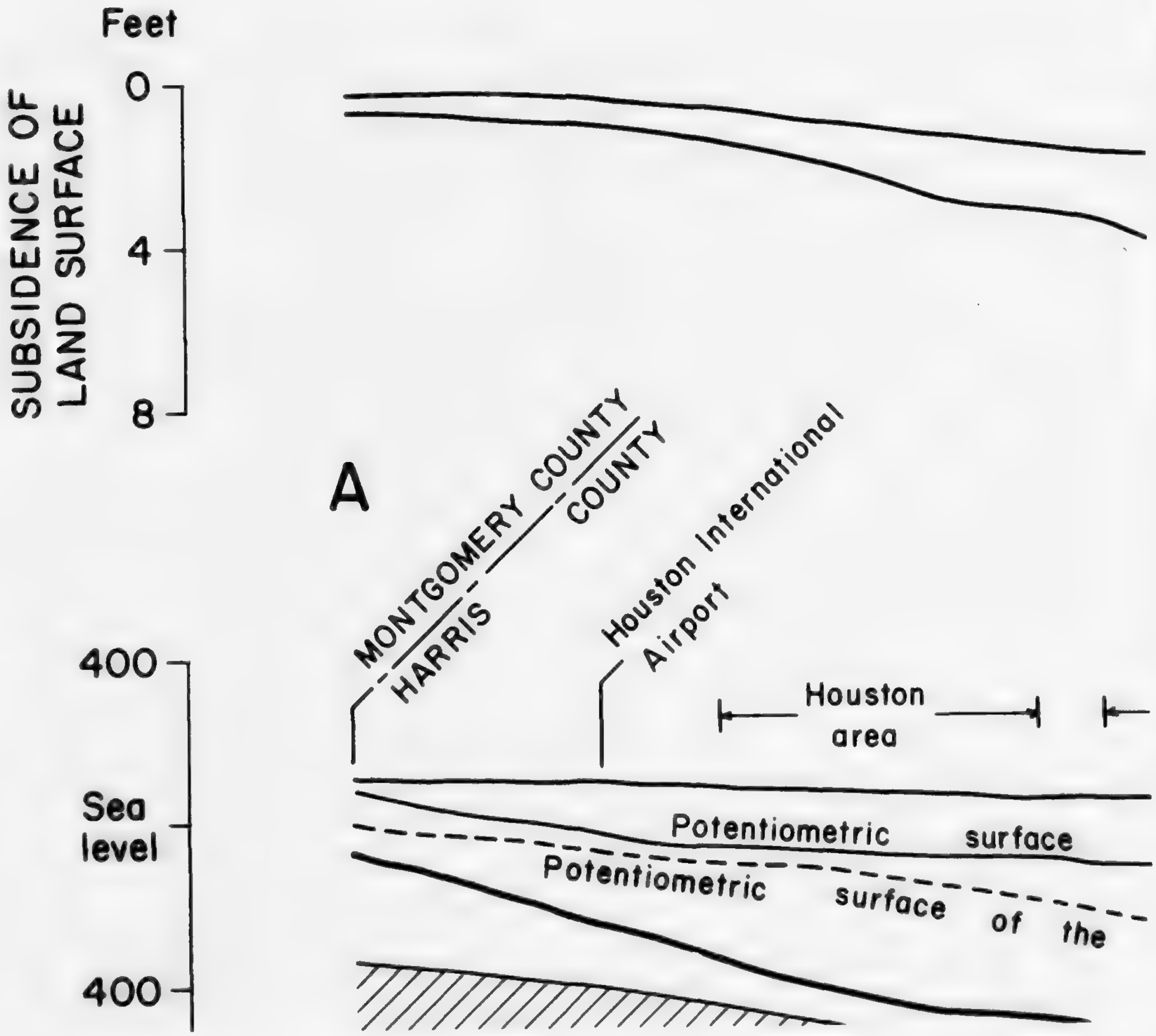

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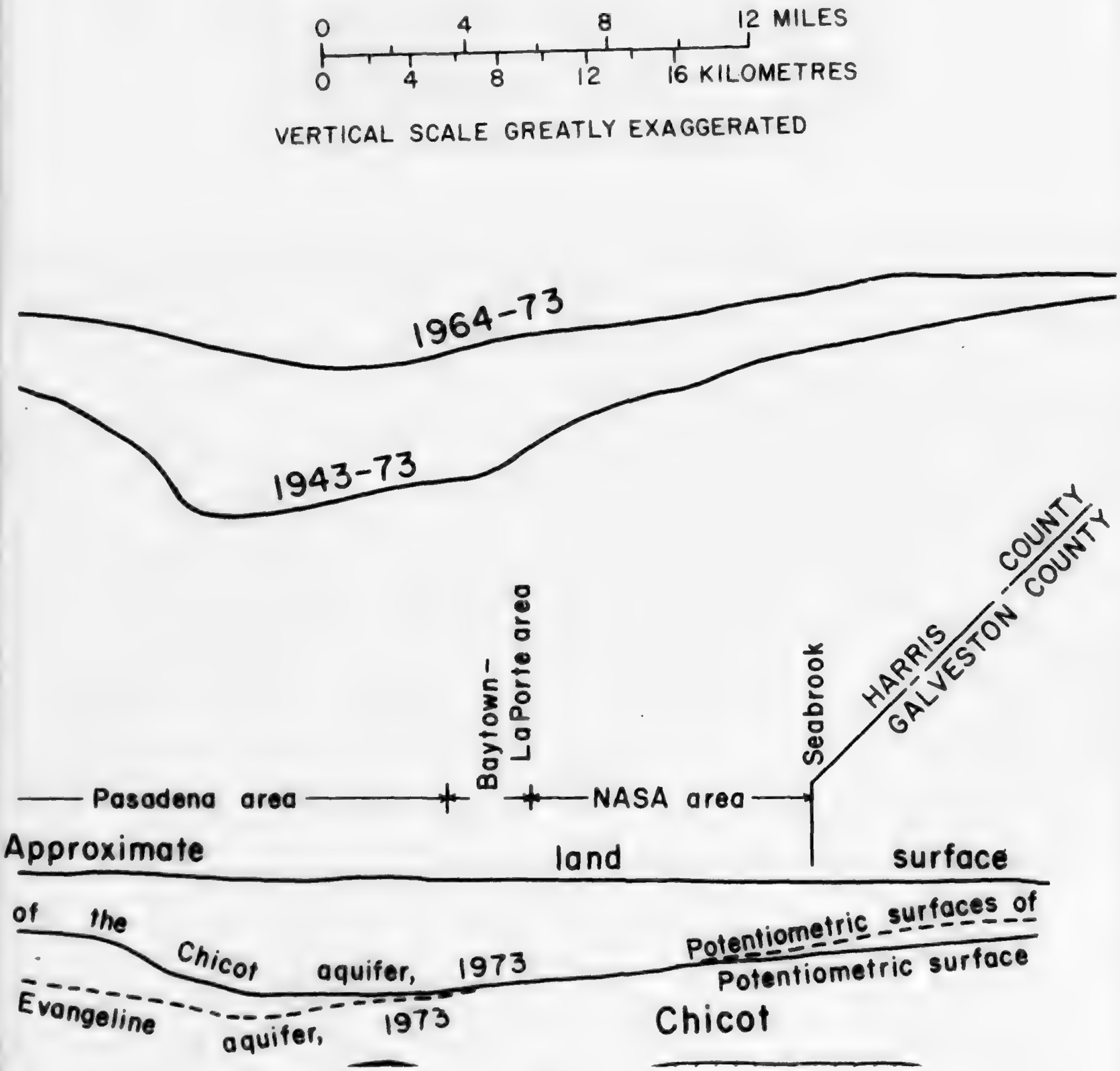
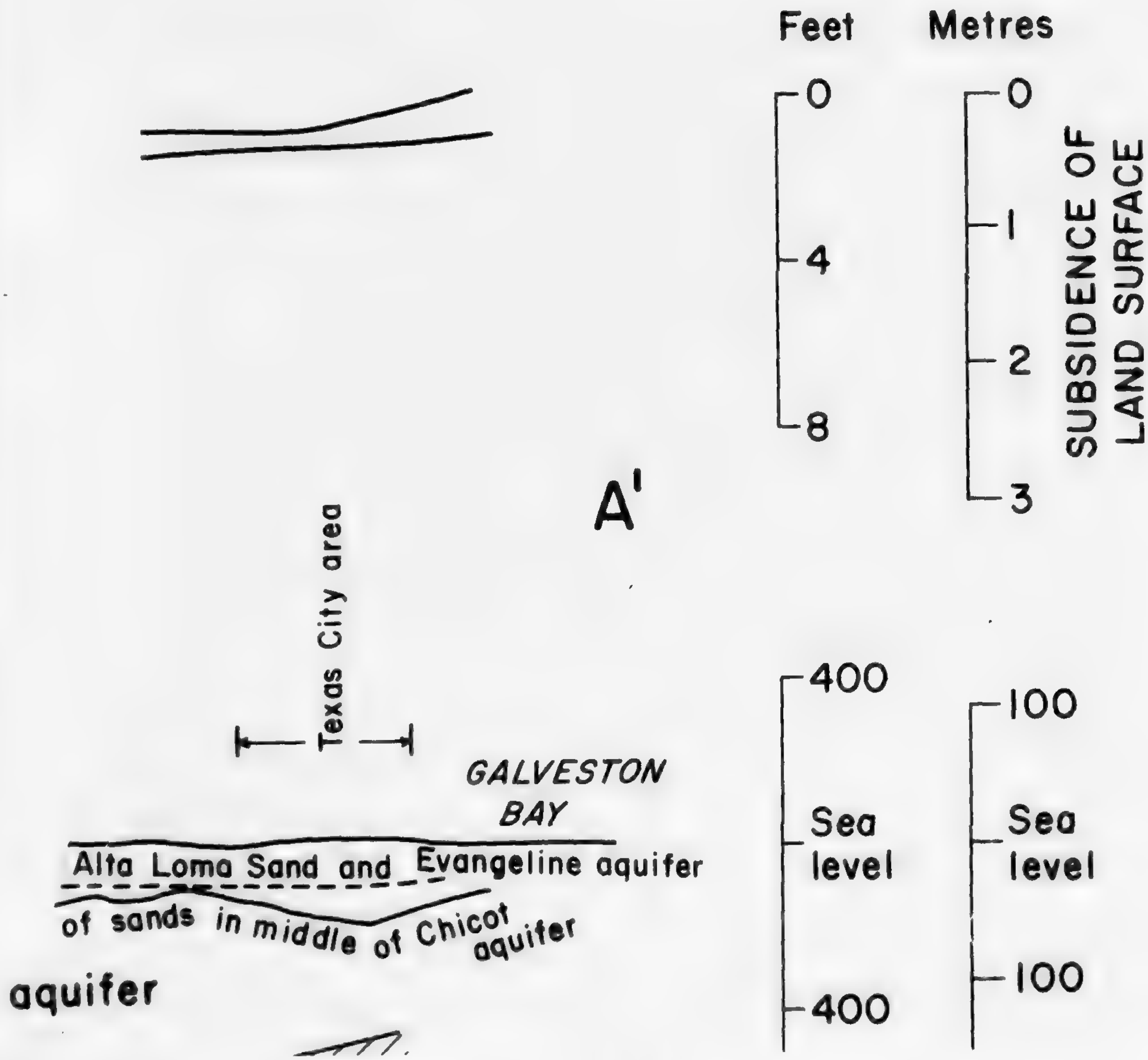
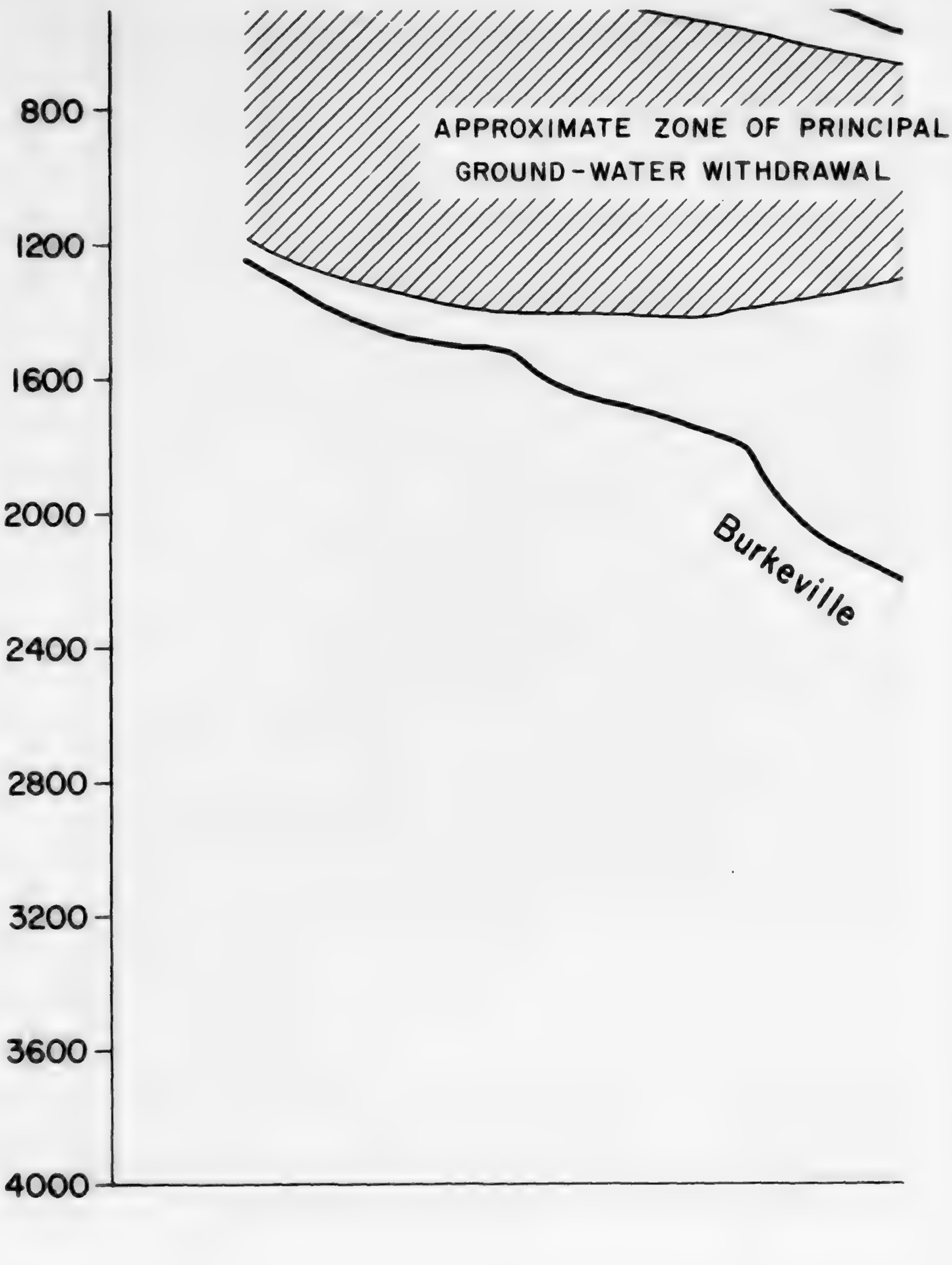
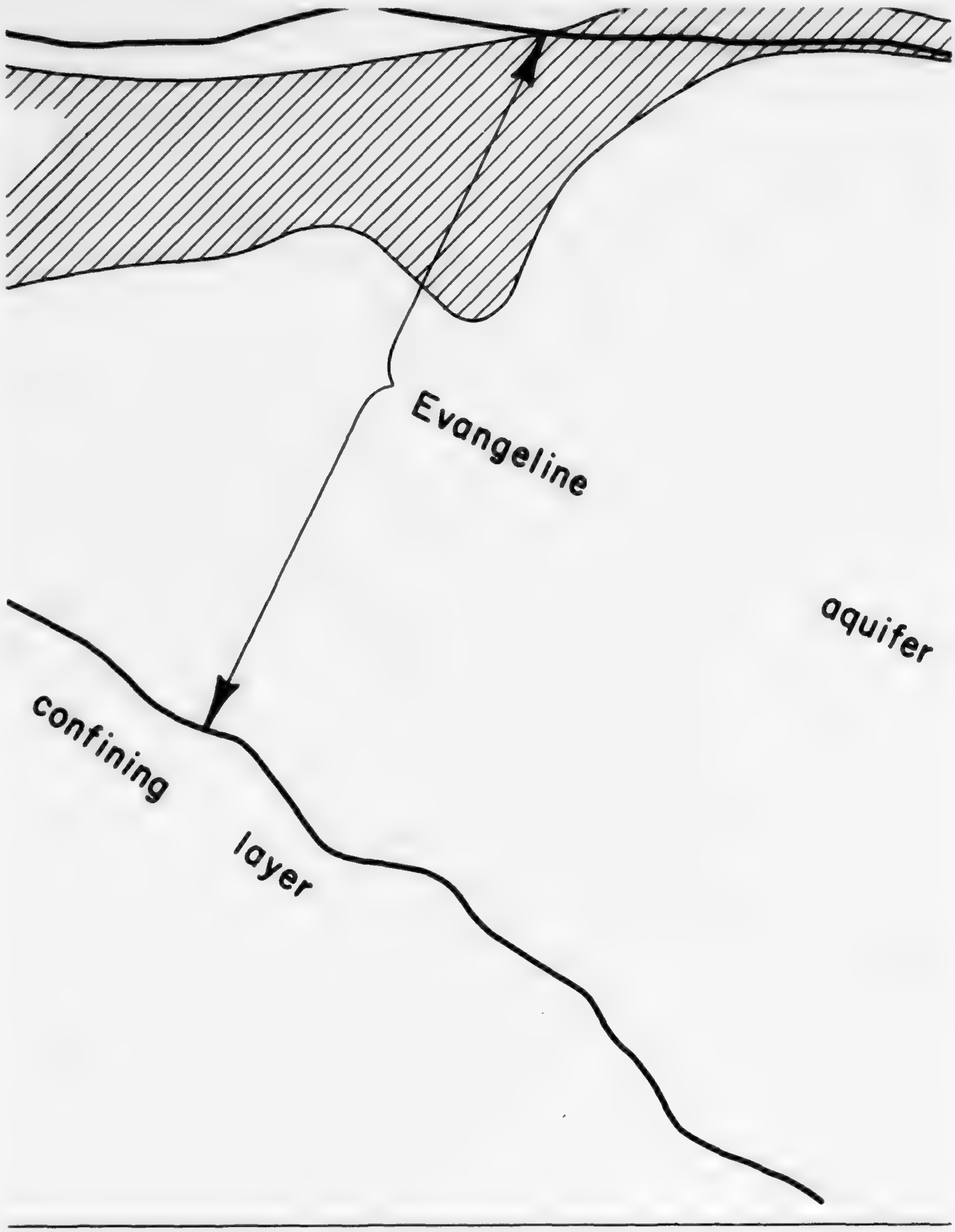
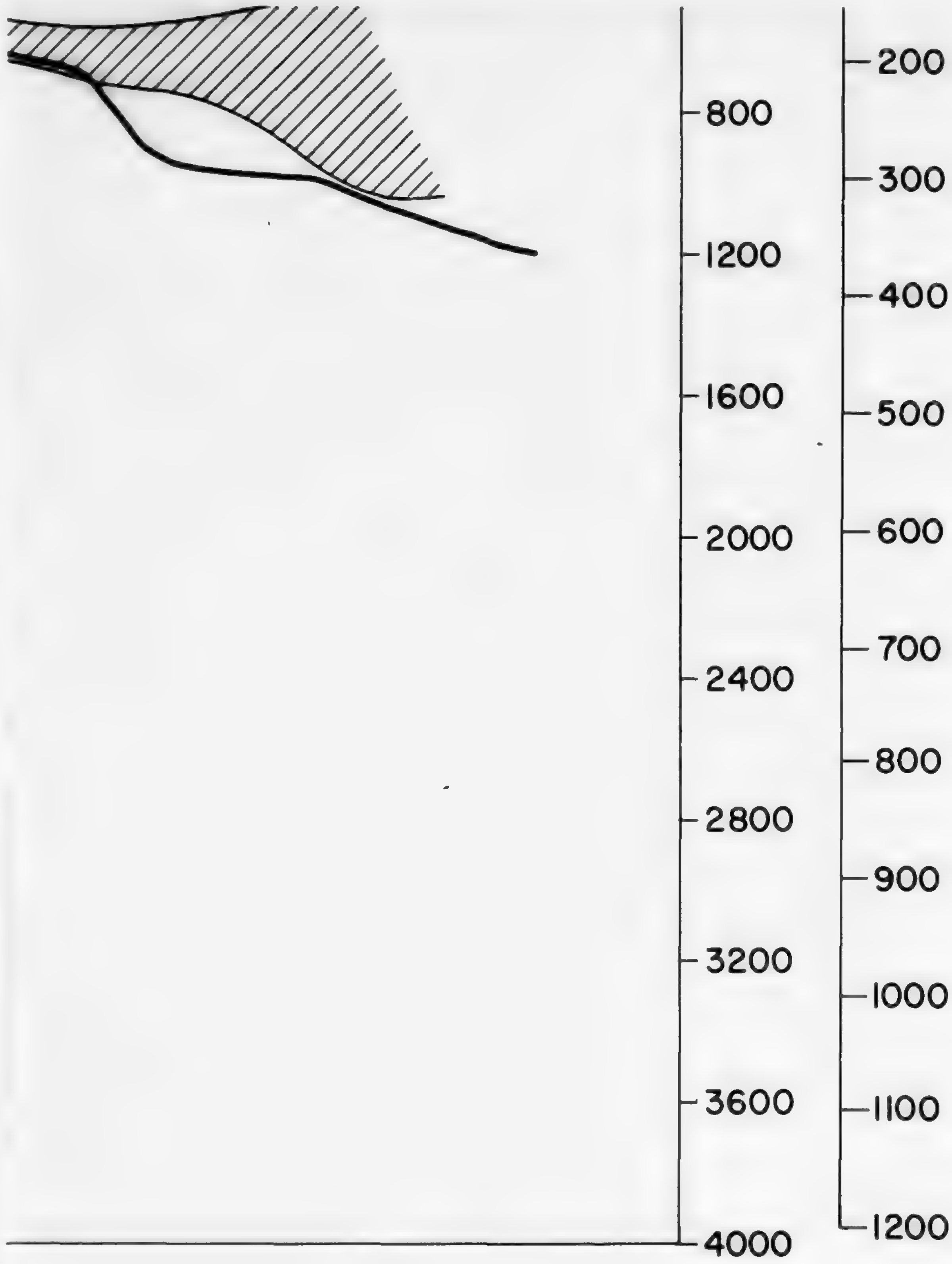



Feet
Metres
0
4
8
0
1
2
3
SUBSIDENCE OF LAND SURFACE
A'
Texas City area
GALVESTON BAY
Alta Loma Sand and
Evangeline aquifer
of sands in middle of Chicot aquifer
aquifer
400
Sea level
400
100
Sea level
100


800
1200
1600
2000
2400
2800
3200
3600
4000
APPROXIMATE ZONE OF PRINCIPAL
GROUND-WATER WITHDRAWAL
Burkeville


Evangeline
aquifer
confining
layer


800
1200
1600
2000
2400
2800
3200
3600
4000
200
300
400
500
600
700
800
900
1000
1100
1200

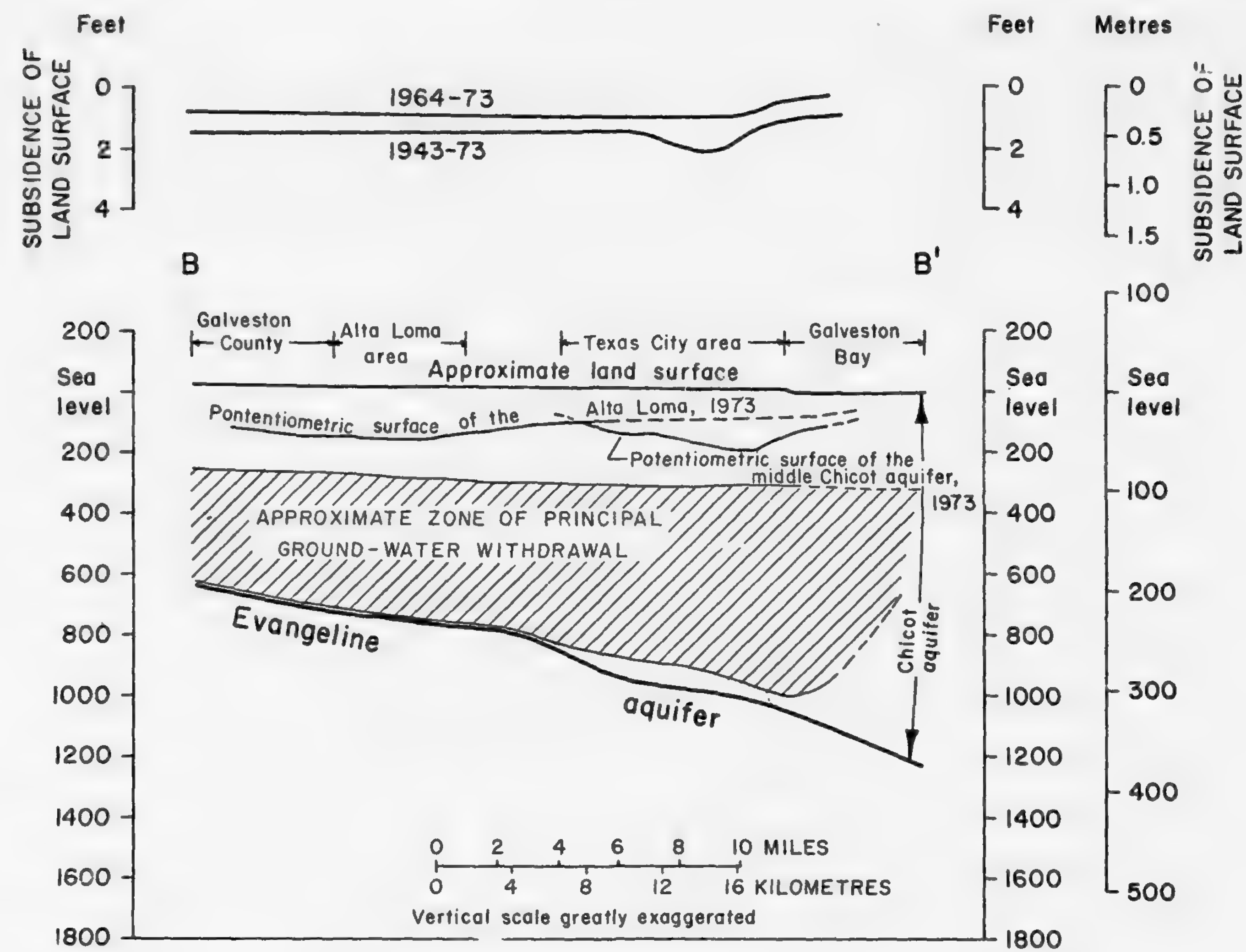
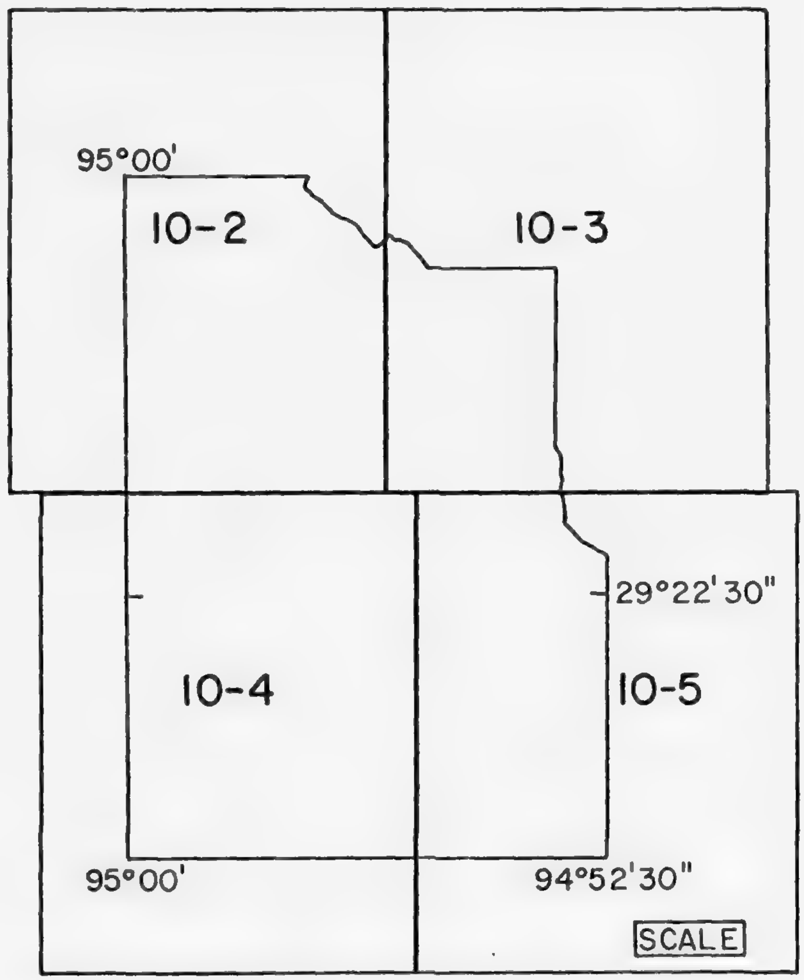


FIGURE 4.-Hydrologic profile B-B' from Alta Loma to Texas City showing aquifers, principal zones of ground-water withdrawal, altitude of the potentiometric surfaces, and land-surface subsidence

FIGURE 5

APPROXIMATE SUBSIDENCE OF THE LAND SURFACE, 1943-73



Index map showing page numbers of each component of figure 5

EXPLANATION

—*3.0*— — LINE OF EQUAL LAND-SURFACE SUBSIDENCE--Interval 0.5 foot (0.15 metre)

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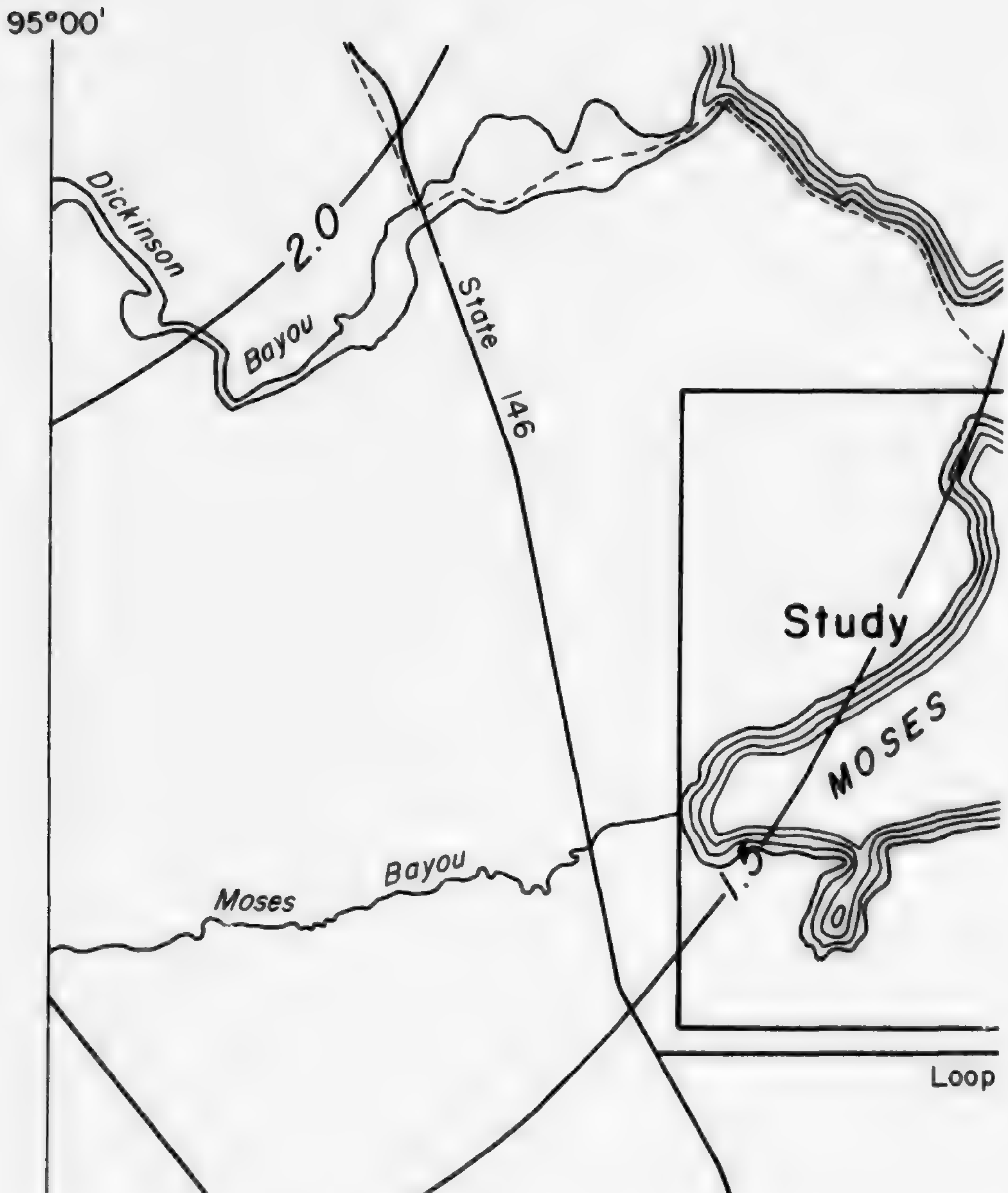

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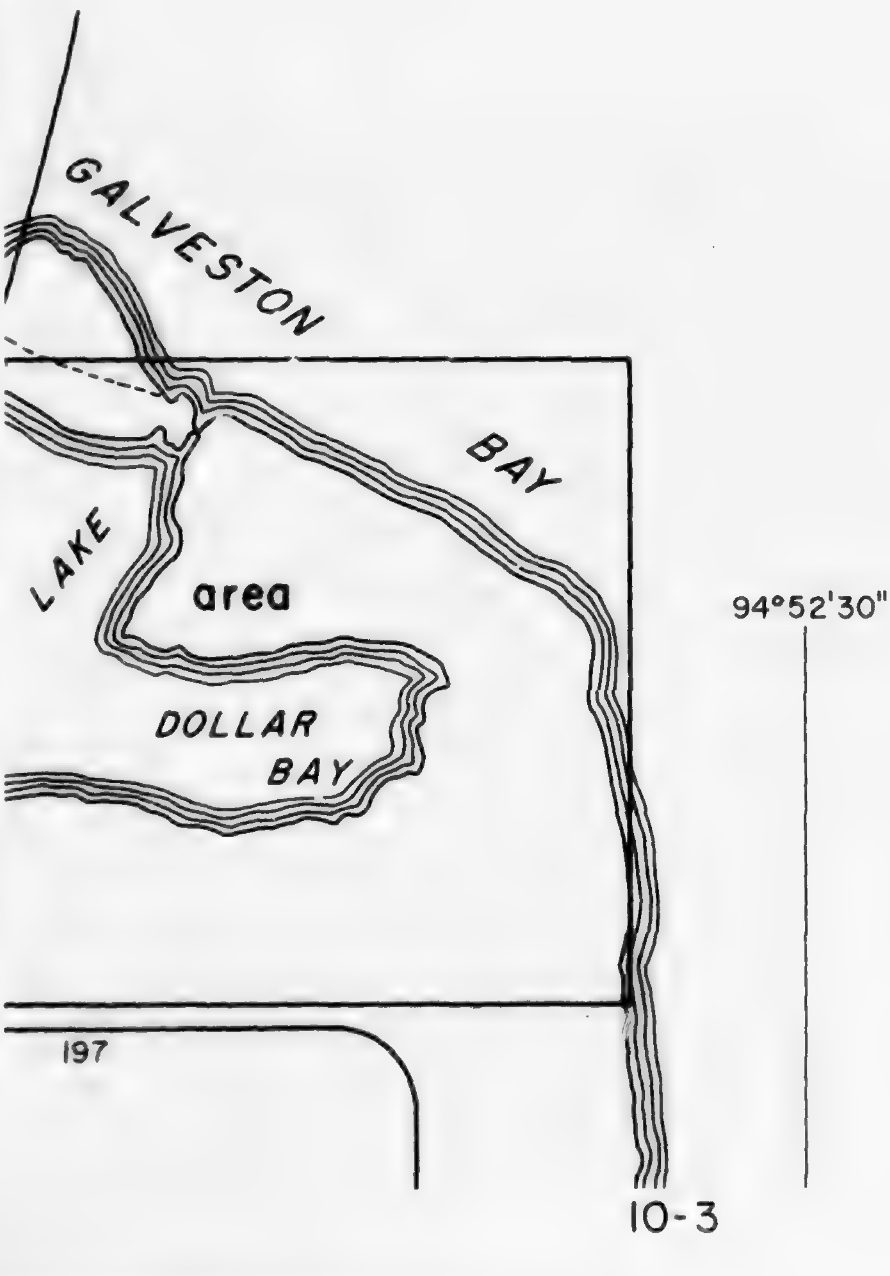
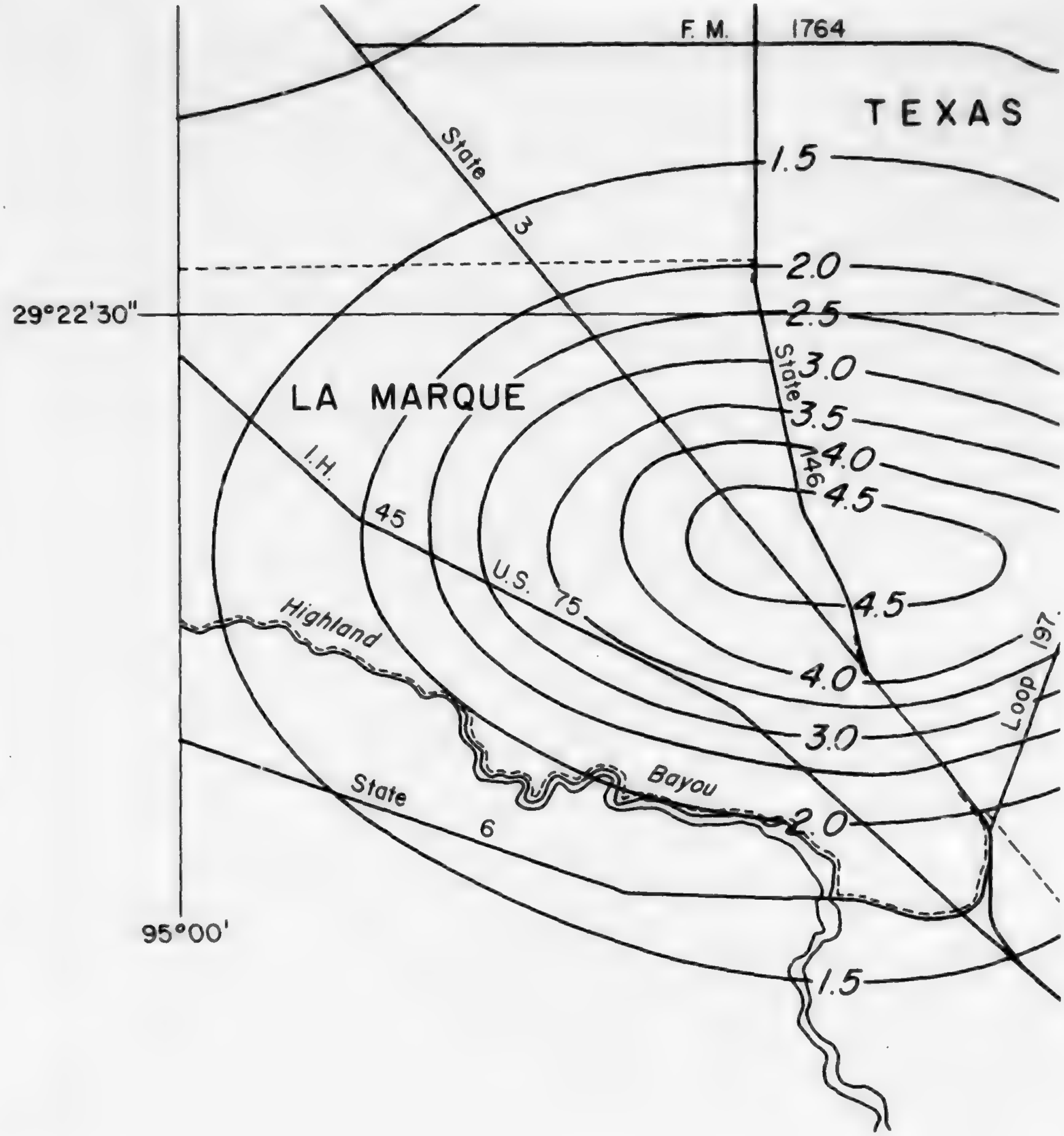




Base from U.S. Geological Survey
topographic quadrangles

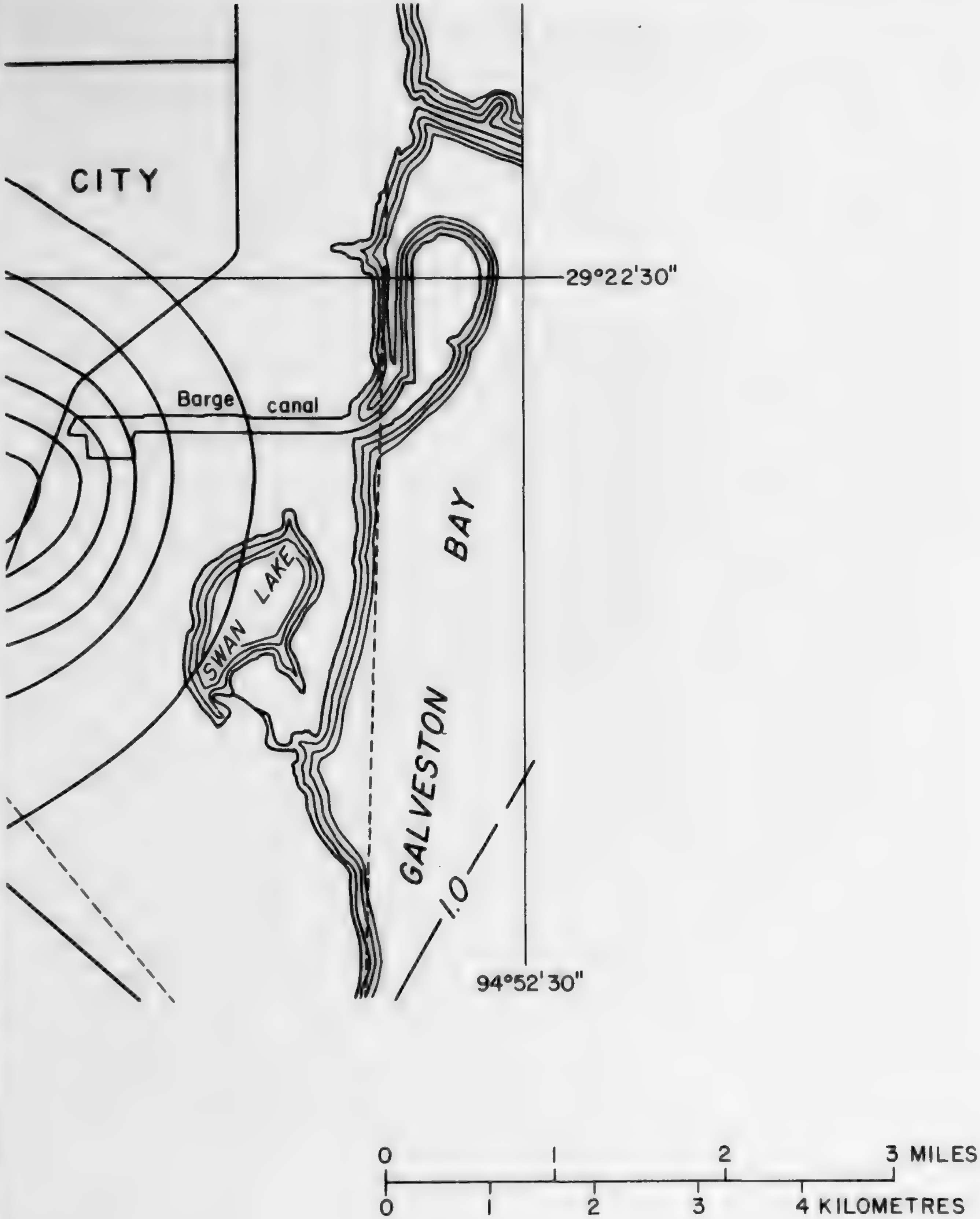
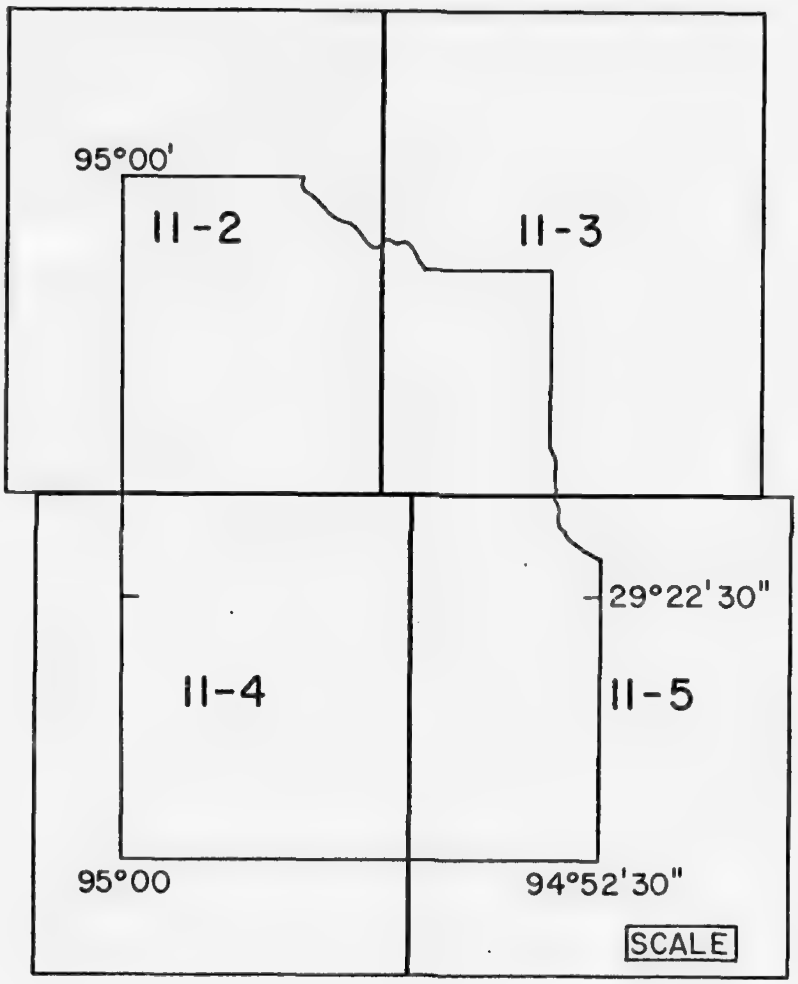

CITY
29°22'30"
Barge canal
SWAN LAKE
BAY
GALVESTON
1.0
94°52'30"
0 1 2 3 MILES
0 1 2 3 4 KILOMETRES

FIGURE 6

APPROXIMATE SUBSIDENCE OF THE LAND SURFACE, 1964-73



Index map showing page numbers of each component of figure 6

EXPLANATION

—3.0—— LINE OF EQUAL LAND-SURFACE SUBSIDENCE--Intervals 0.1 and 0.5 foot (0.03 and 0.15 metre)

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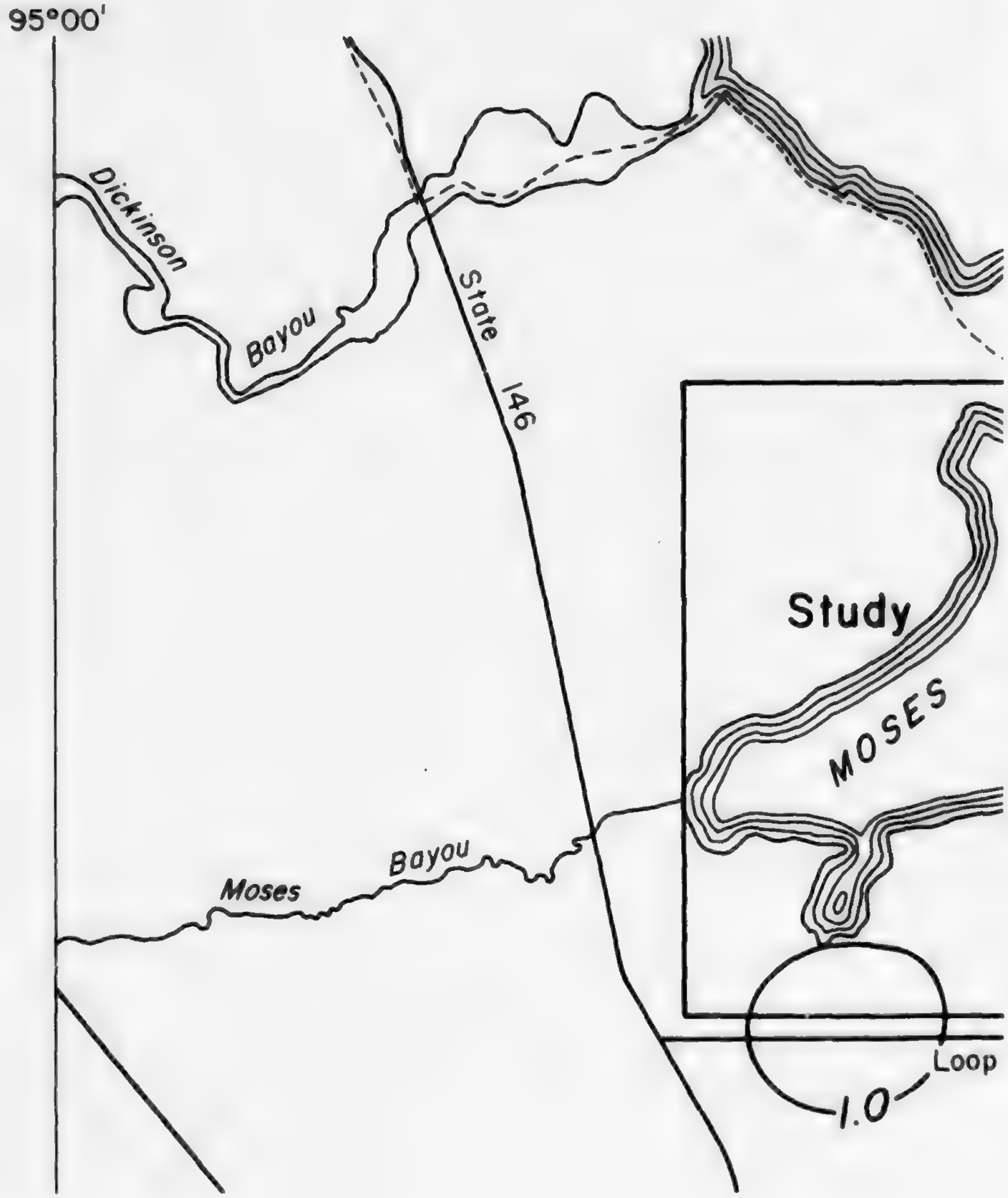

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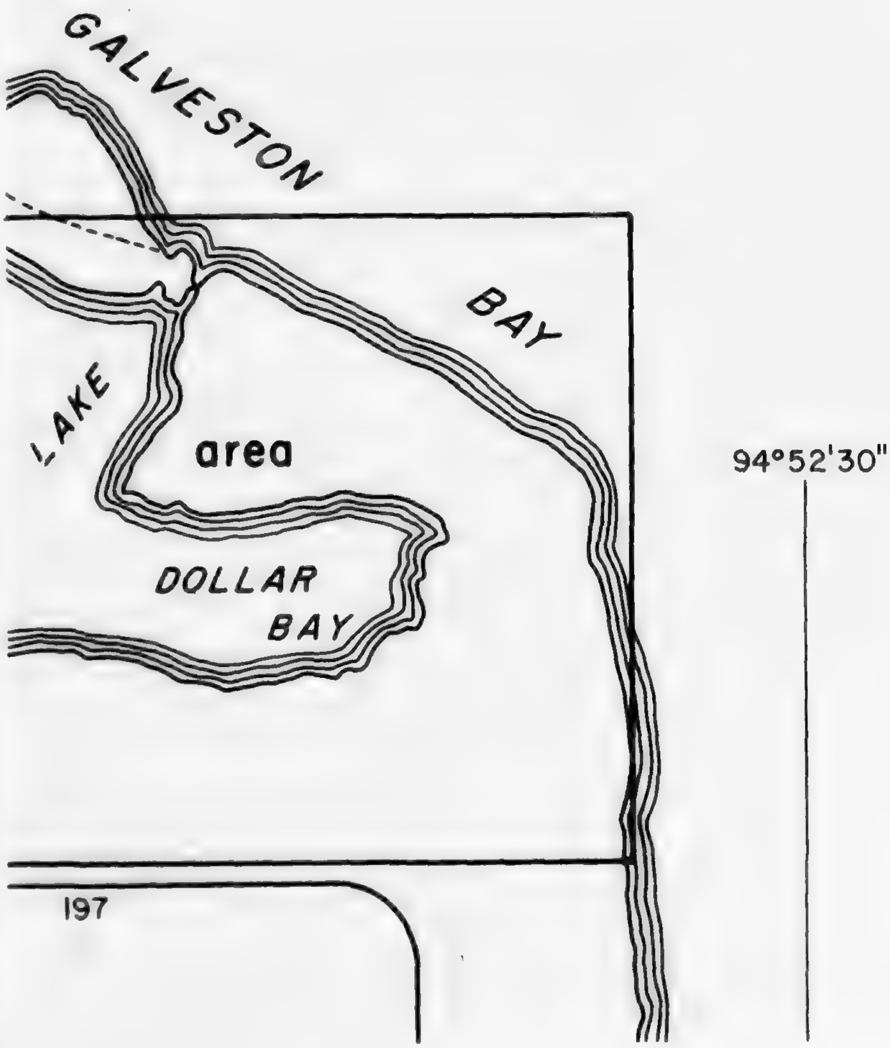
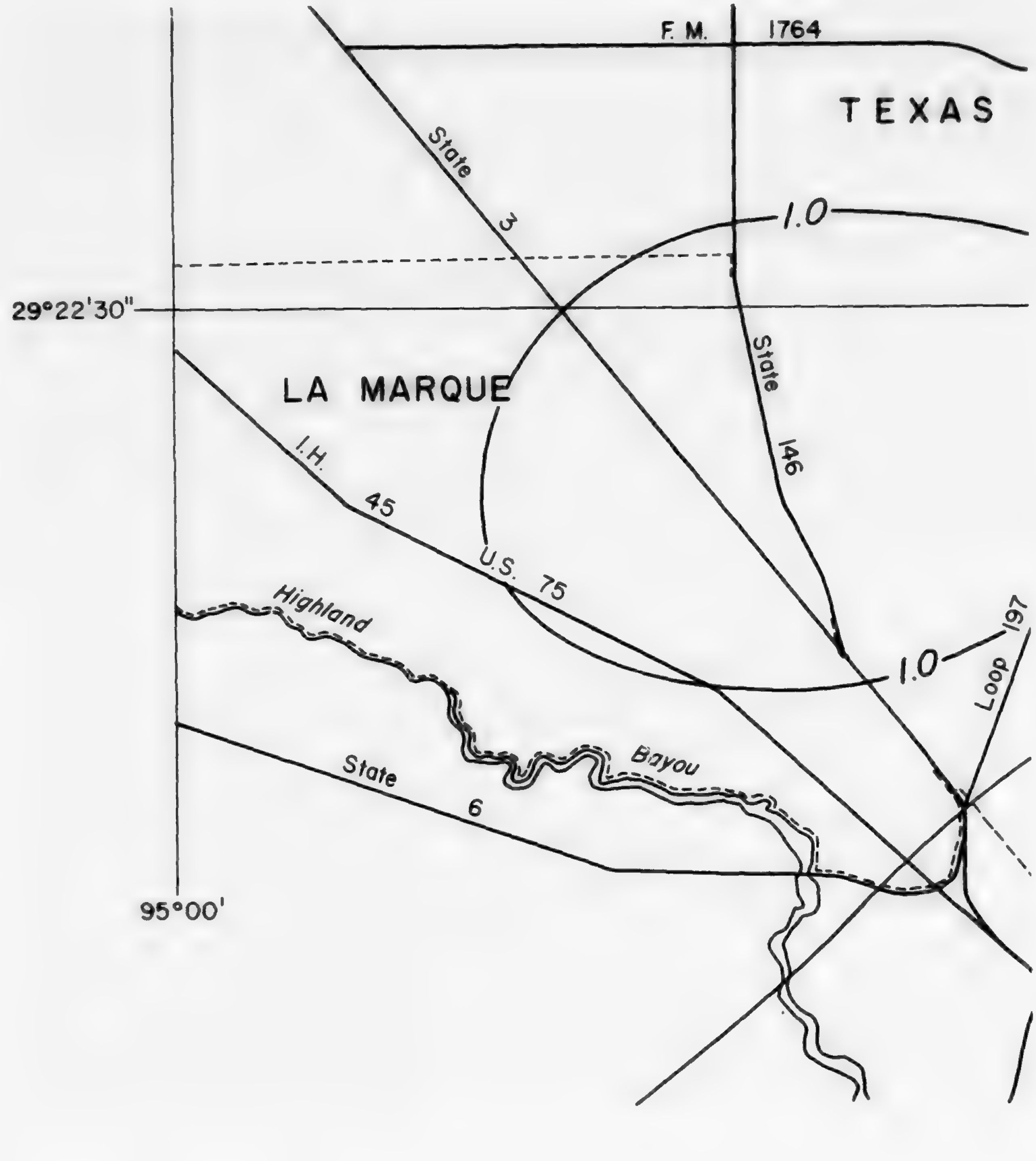
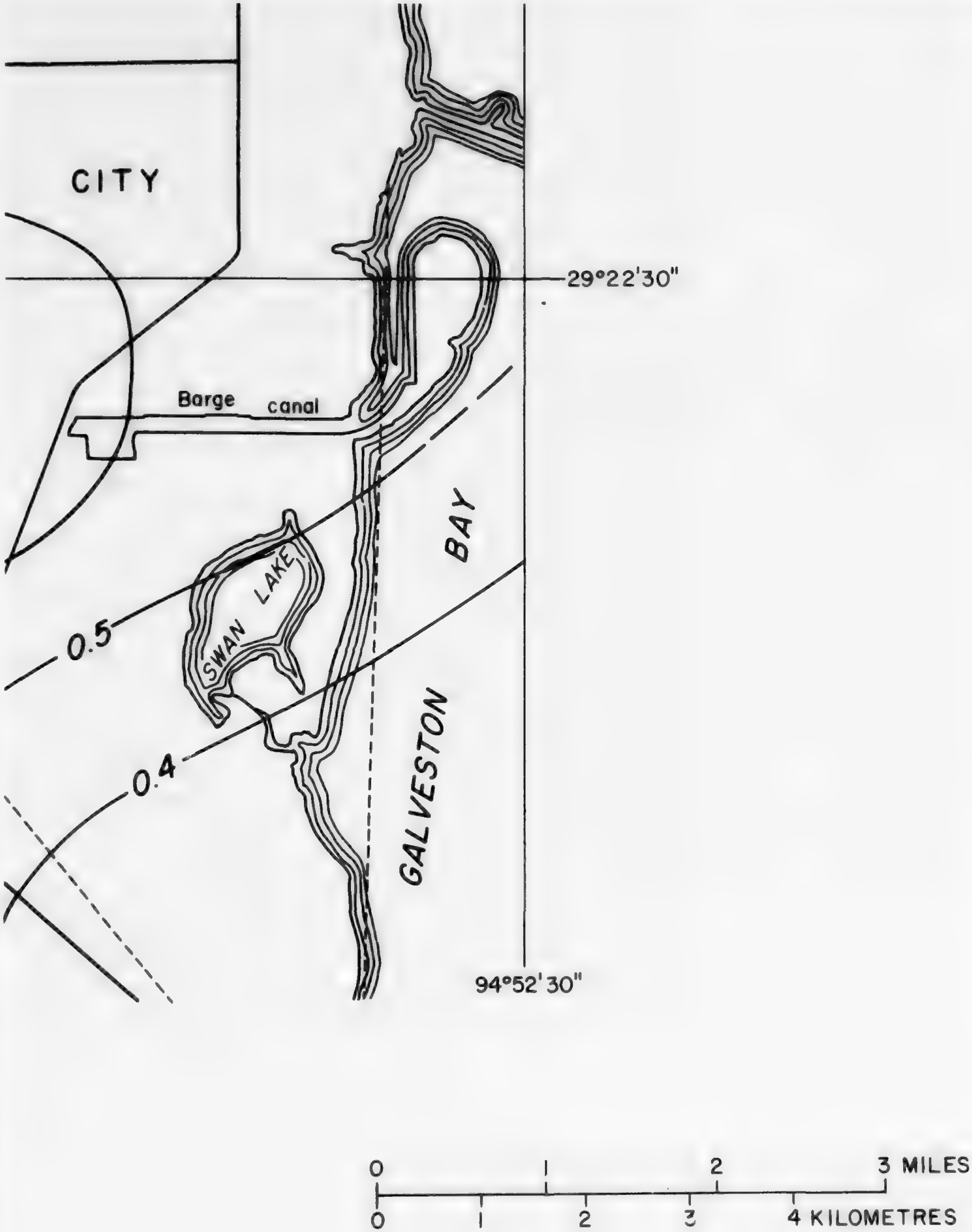




Base from U.S. Geological Survey
topographic quadrangles


CITY
29°22'30"
Barge canal
SWAN LAKE
BAY
0.5
GALVESTON
0.4
94°52'30"
0 1 2 3 MILES
0 1 2 3 4 KILOMETRES

Subsidence in Texas City began in the late 1930's, and by 1943 as much as 1.6 feet (0.49 m) had occurred in the industrial area (Gabrysch and Bonnet, 1974b). The tabulations in the American Oil Company report (1958, Section A, table 1, p. 6) show that during the period 1943-52, the rates of subsidence at four bench marks in the industrial area ranged from 0.213 to 0.336 foot (0.065 to 0.102 m) per year. The decreases in ground-water withdrawals after the introduction of surface water in 1948 resulted in some recovery of artesian heads in the Chicot aquifer and greatly decreased the rate of subsidence. The American Oil Company data, however, were not sufficient for determination of the rate of subsidence that occurred immediately prior to the increase in the use of surface water. In all probability, the rate of subsidence was significantly higher than that indicated at the four bench marks--in each of the two 5-year periods 1954-58 and 1959-63, the average rate of subsidence was only 0.04 to 0.06 foot (0.012 to 0.018 m) per year.

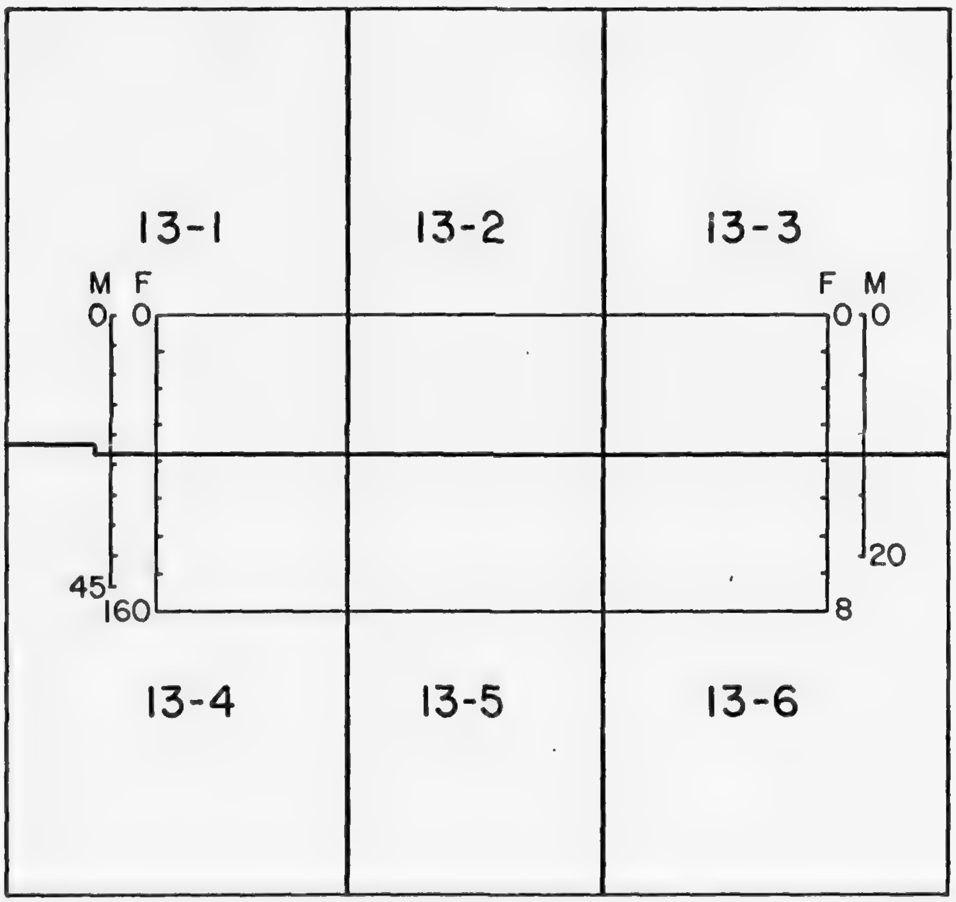
Since 1964, a gradual increase in ground-water pumping in the Texas City area and the effects of pumping outside the area caused water levels to decline below their 1948 levels. An accelerated rate of land-surface subsidence is now occurring (1975). Figure 6 shows that about 1.0 foot (0.30 m) of subsidence occurred between 1964 and 1973, which is a rate of about 0.11 foot (0.034 m) per year.

The Moses Lake study area is about 4 miles (6.4 km) north of the central part of the industrial area of Texas City. Subsidence in the study area has been much less than in the industrial area. About 0.4 foot (0.122 m) of subsidence occurred in the study area before 1943 (Gabrysch and Bonnet, 1974b) and about 1.4 feet (0.43 m) between 1943 and 1973 (fig. 5). About 0.6 foot (0.183 m) of the 1.4 feet (0.43 m) occurred during 1964-73 (fig. 6).

The change in artesian heads and subsidence of the land surface are shown on figures 7 and 8. Figure 7 shows plots of measurements of water levels in three wells and changes in the elevation of bench mark X305, which is about 5 miles (8 km) south of Moses Lake (fig. 1). Data illustrating the recovery in artesian head in response to the decrease in ground-water pumping in 1948 were not available within the study area. Figure 8 depicts an approximation of the head changes and subsidence at Moses Lake on the basis of interpretations of regional water-level decline and subsidence maps. The original artesian heads in the middle Chicot aquifer, the Alta Loma Sand, and the Evangeline aquifer are assumed values. It should be emphasized that the graphs on figure 8 are a representation of composite declines in each aquifer and are presented to illustrate the general relationship.

FIGURE 7

HYDROGRAPHS SHOWING CHANGES IN WATER LEVELS IN WELLS AND GRAPH SHOWING SUBSIDENCE OF BENCH MARK X305



Index diagram showing page numbers of each component of figure 7

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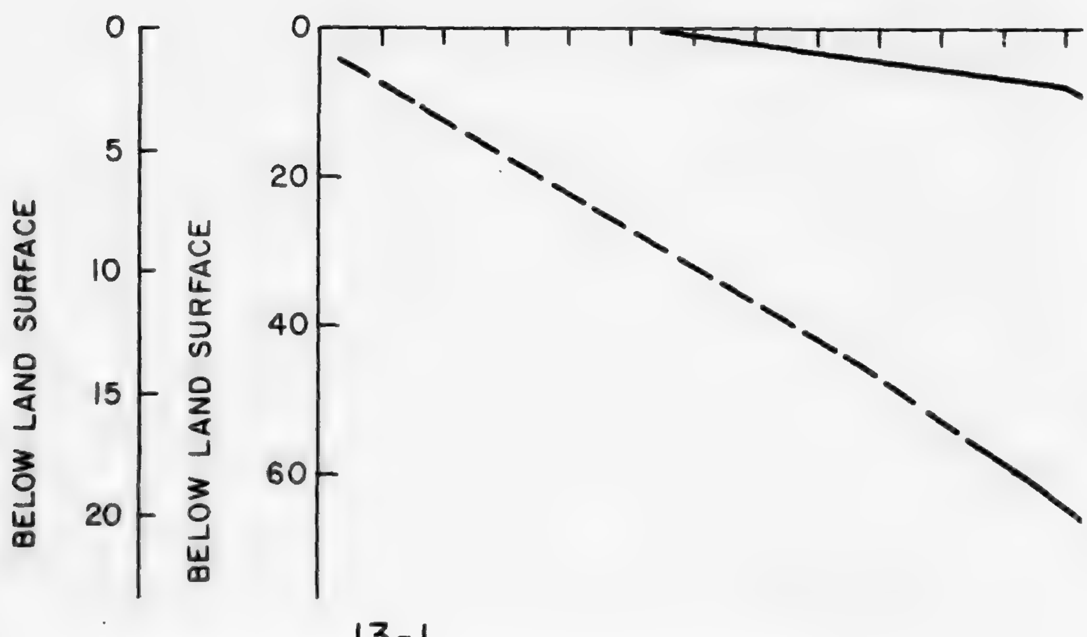

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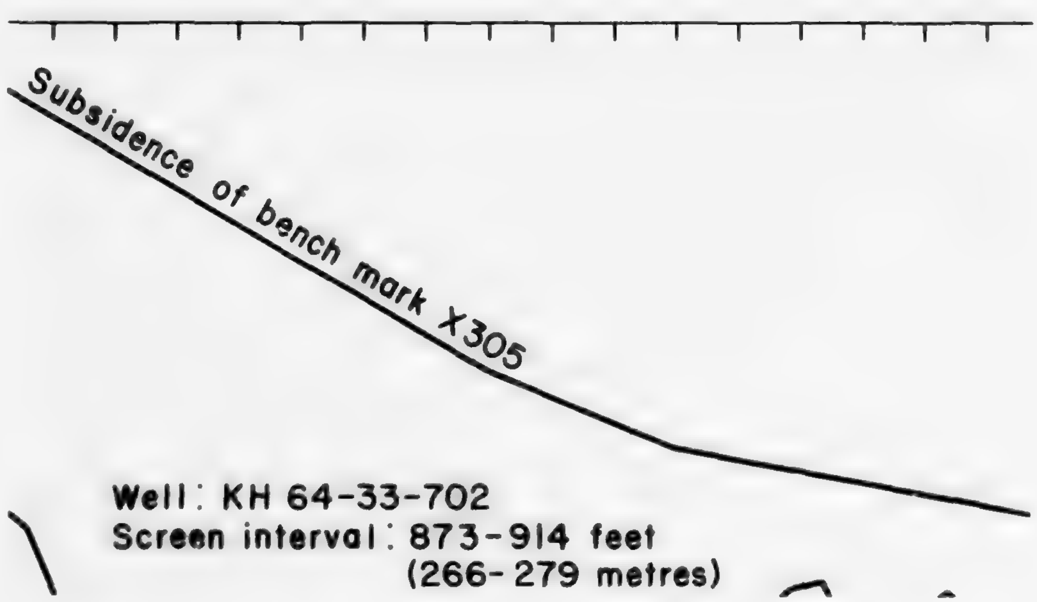
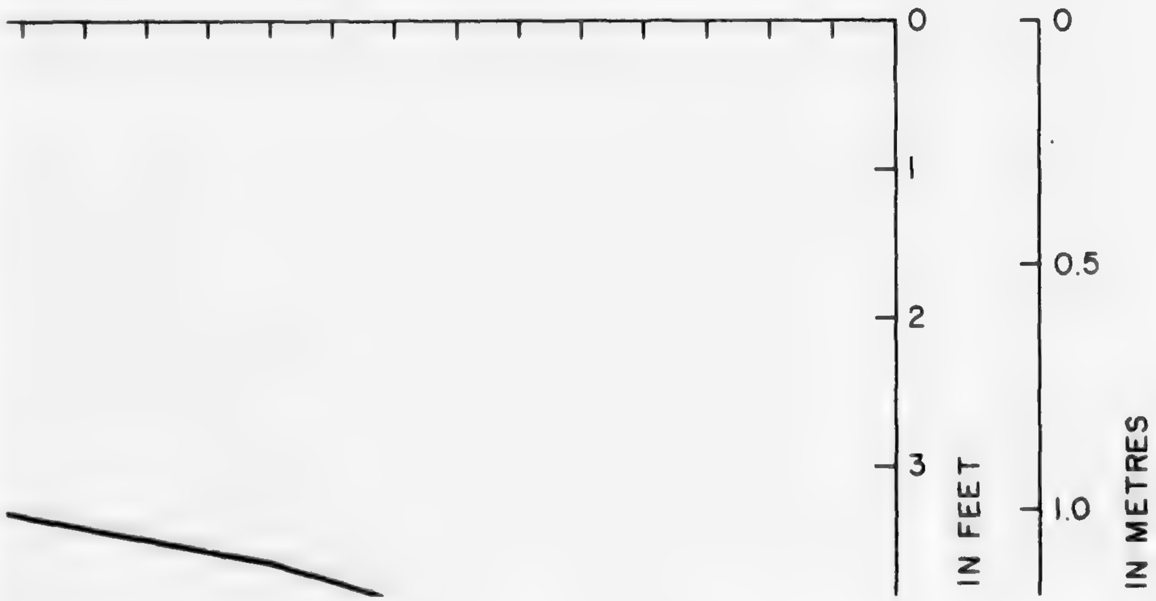
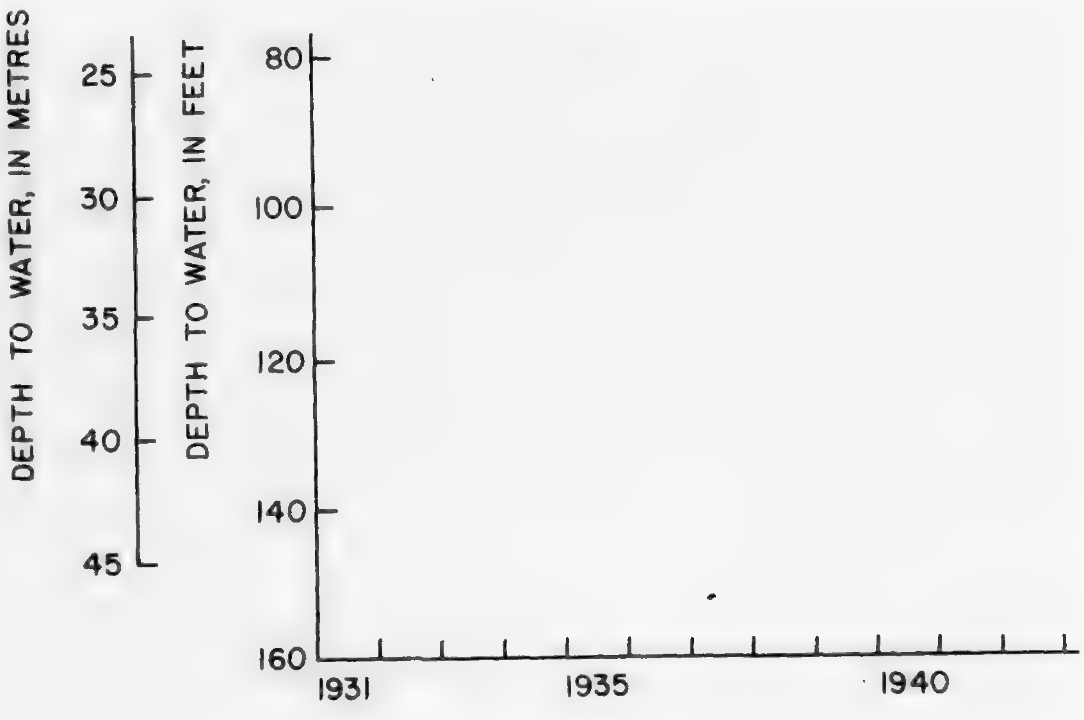
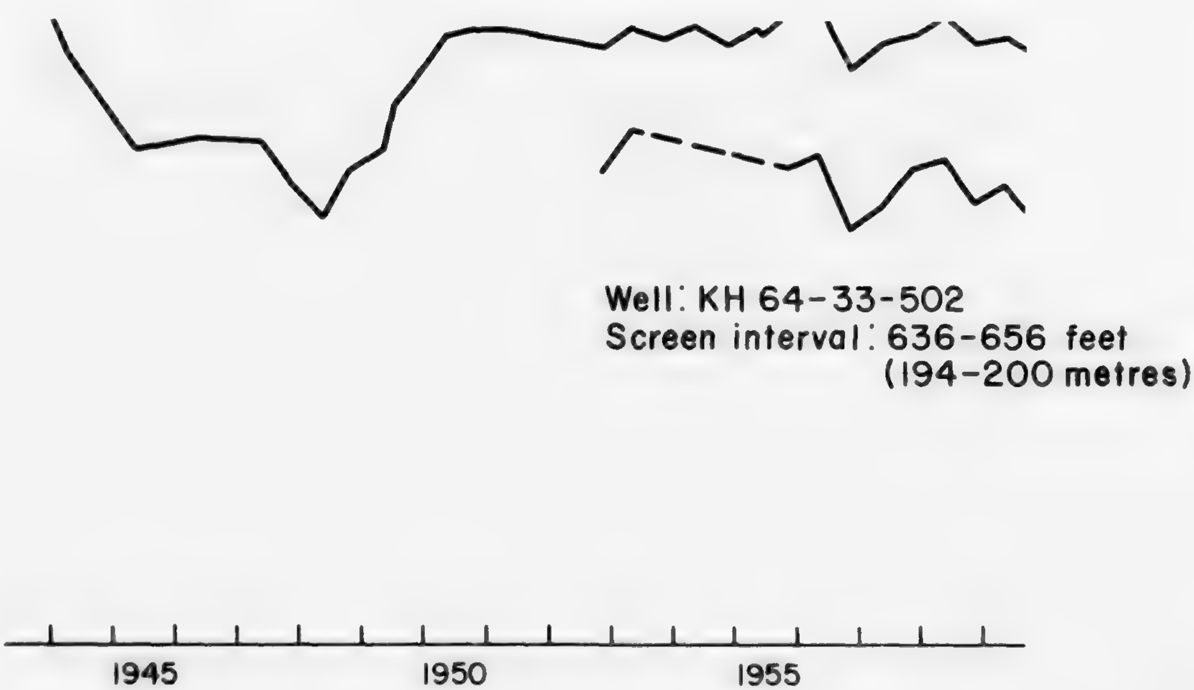
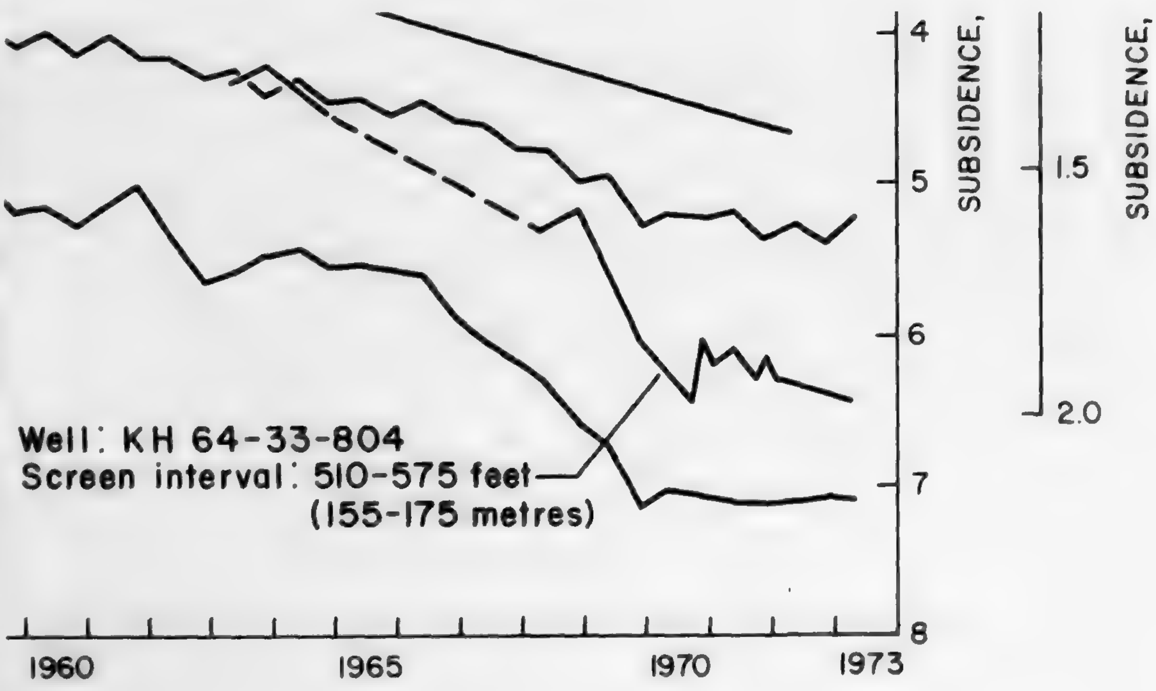



0
1
2
3
IN FEET
0
0.5
1.0
IN METRES


DEPTH TO WATER, IN METRES
25
30
35
40
45
DEPTH TO WATER, IN FEET
80
100
120
140
160
1931
1935
1940


Well: KH 64-33-502
Screen interval: 636-656 feet
(194-200 metres)
1945
1950
1955


Well: KH 64-33-804
Screen interval: 510-575 feet
(155-175 metres)
4
5
6
7
8
SUBSIDENCE,
1.5
2.0
SUBSIDENCE,
1960
1965
1970
1973

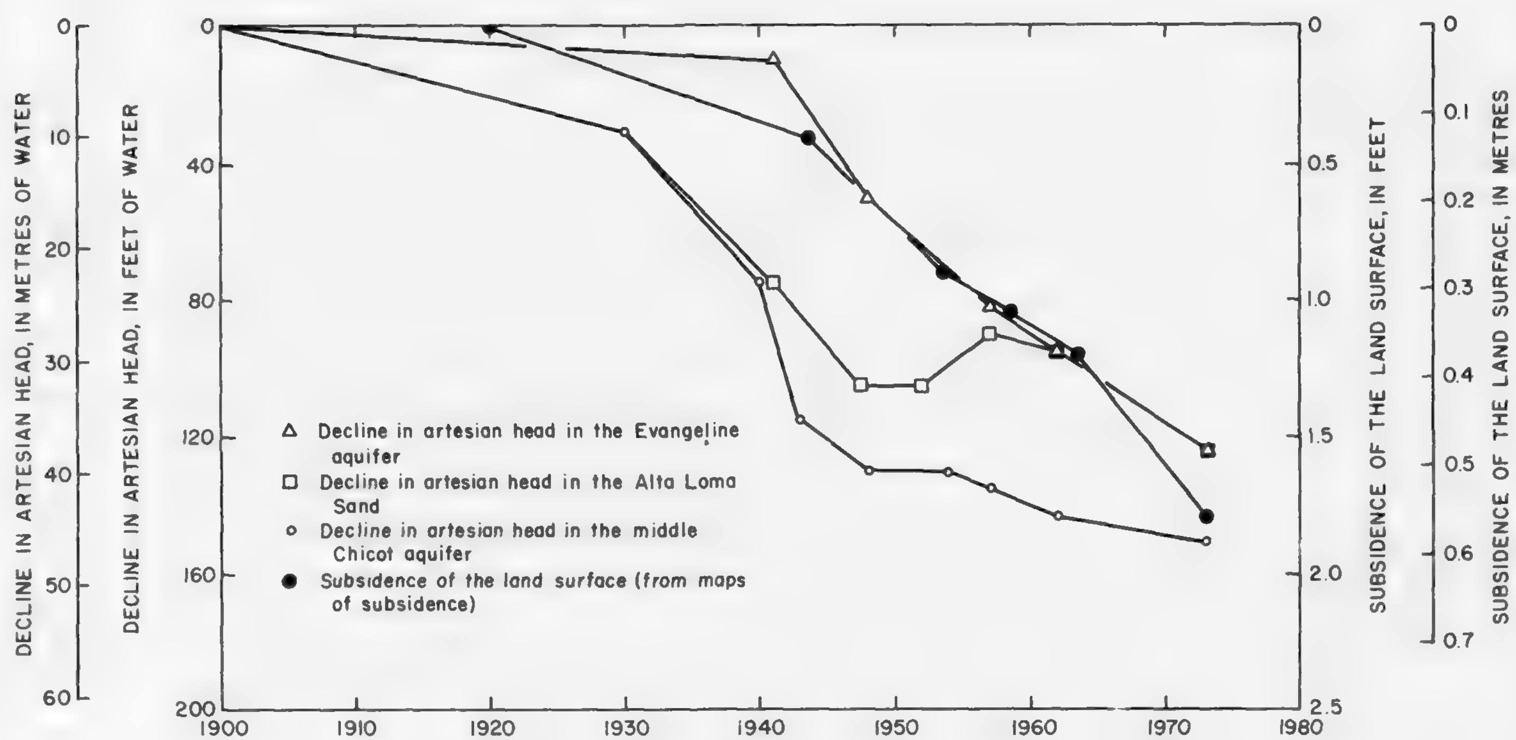


FIGURE 8.-Land-surface subsidence and artesian-head decline at Moses Lake

DATA COLLECTION AND ANALYSIS

This study of land-surface subsidence required the collection and analysis of data from boreholes. It was necessary to select a drilling and monitoring site that was near the study area and where instrumentation could be protected from vandalism. The site selected is in the fenced yard of a sewage-treatment plant near the hurricane-tide protection levee, 2.5 miles (4 km) from the mouth of Moses Lake (fig. 1).

Seven wells (KH 64-33-915 to 921, fig. 1) were drilled at the test site for this study; the depths of the wells are 24, 210, 302, 400, 535, 790, and 1,060 feet (7, 64, 92, 122, 163, 241, and 323 m). Water levels are being measured in all seven wells. A borehole extensometer was installed in well KH 64-33-920 to monitor compaction of the material between land surface and a depth of 800 feet (244 m). Records of compaction at this site and at three other sites in the Houston-Galveston region are shown on figure 9.

Probably most of the subsidence at Moses Lake is due to compaction of material above the Alta Loma Sand; therefore, the extensometer record should be valuable for estimating subsidence on a continuing basis. Six wells, KH 64-33-915 to 920, were drilled by conventional rotary methods; and one well, KH 64-33-921, was drilled by a truck-mounted auger. Drillers' logs, chemical analyses of water samples, water-level measurements, and well-completion records for these wells are given in a separate report (Naftel, Vaught, and Fleming, 1975).

An electrical log run in well KH 64-33-919 at the test site and logs from nearby wells were used to determine the thickness of the clay beds. Figure 10 shows the log of a well at the site and at a nearby well used in the interpretation. On the basis of these logs, the clays from the land surface to a depth of 1,660 feet (506 m) were grouped into 62 layers (table 4). The clay beds in the layers ranged in thickness from 2 feet (0.6 m) to 24 feet (7.3 m). Forty-four of the beds were less than 10 feet (3.0 m) thick. A small amount of compaction probably occurs in the lower part of the Evangeline aquifer in the depth interval, 1,700-4,900 feet (518-1,414 m).

Because compaction of the subsurface material is dependent in part on the characteristics of the fine-grained material (chiefly clay) that is being compacted, undisturbed clay samples were collected in well KH 64-33-920 at depths of 163, 256, 423, 512, 619, and 700 feet (50, 78, 129, 156, 189, and 213 m). Six samples were analyzed by the U.S. Geological Survey laboratory in Denver, Colorado, to determine Atterburg limits, moisture content, and unit weights. Consolidation tests were made as part of the analysis and the specific storage and hydraulic conductivity of each sample were determined. Results of the laboratory tests are shown on figures 11-16 and given in tables 1-3. Test data for samples obtained in a subsidence study at Seabrook, Texas, were used to analyze the clay material below the base of the Chicot aquifer.

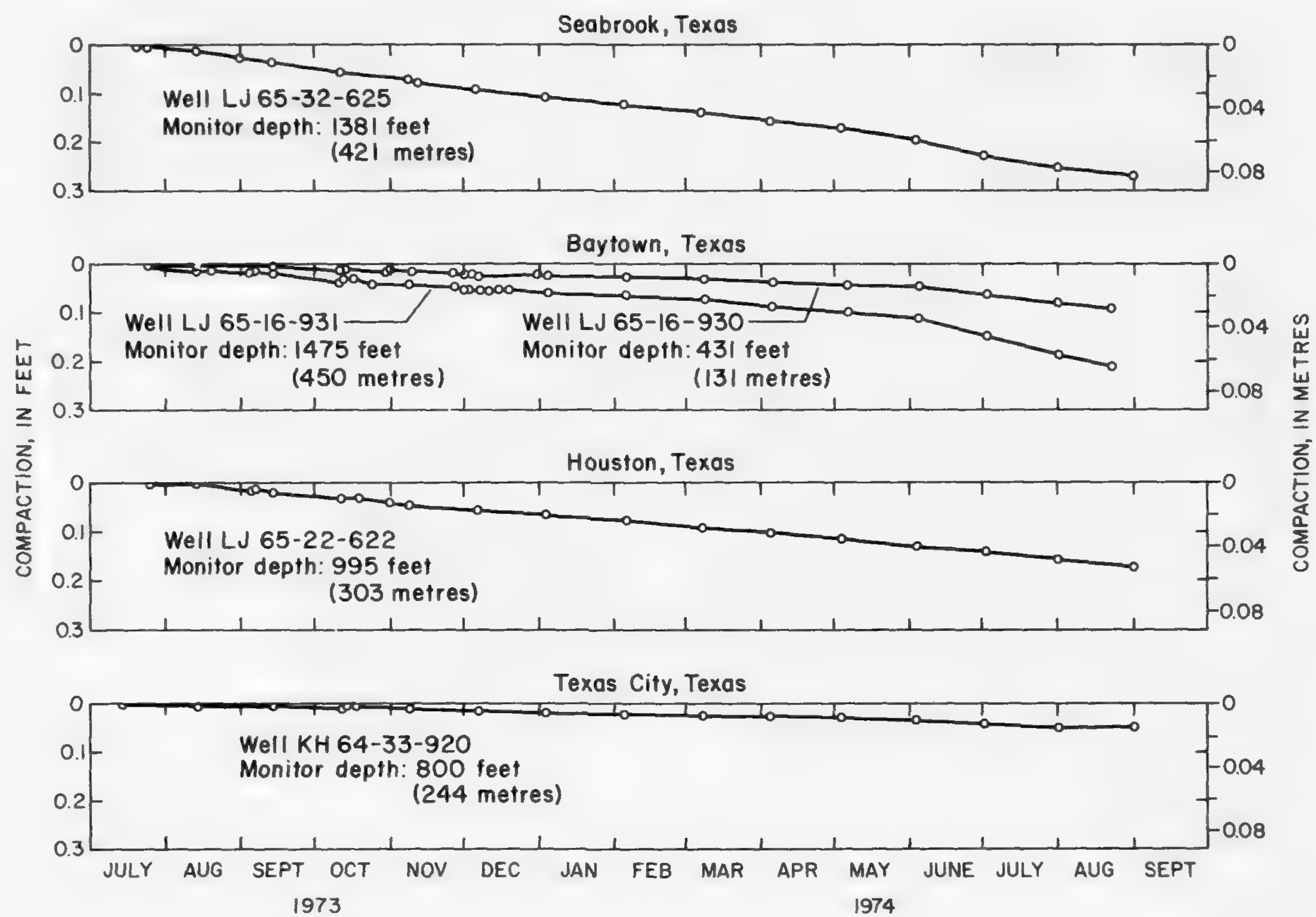
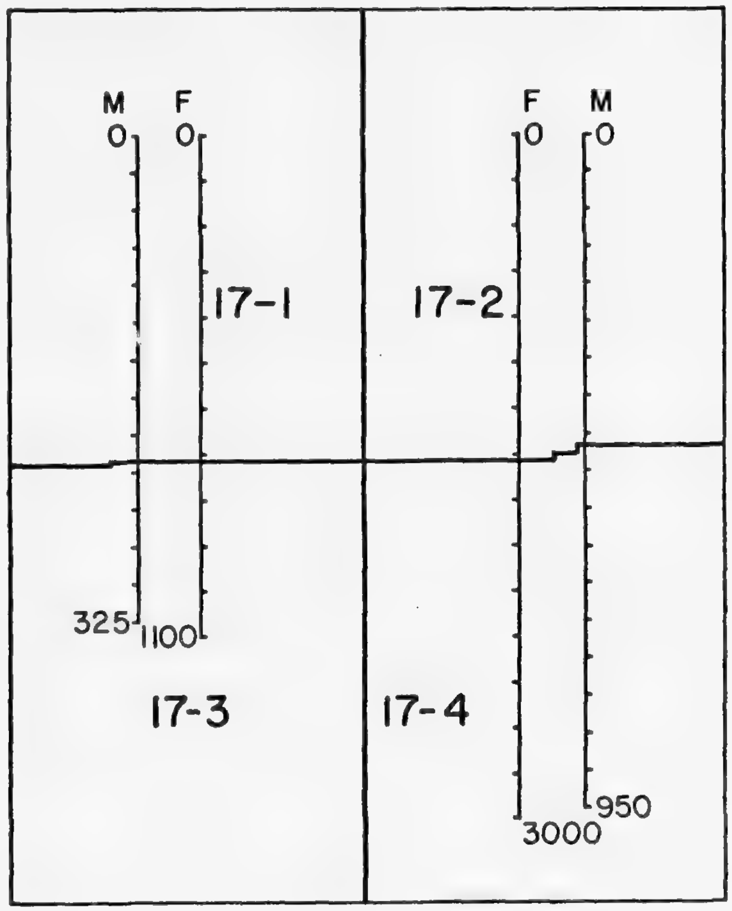


FIGURE 9.-Measured compaction at four sites in the Houston-Galveston region, July 1973 to August 1974

FIGURE 10

ELECTRICAL LOGS OF WELLS IN THE STUDY AREA



Index diagram showing page numbers of each component of figure 10

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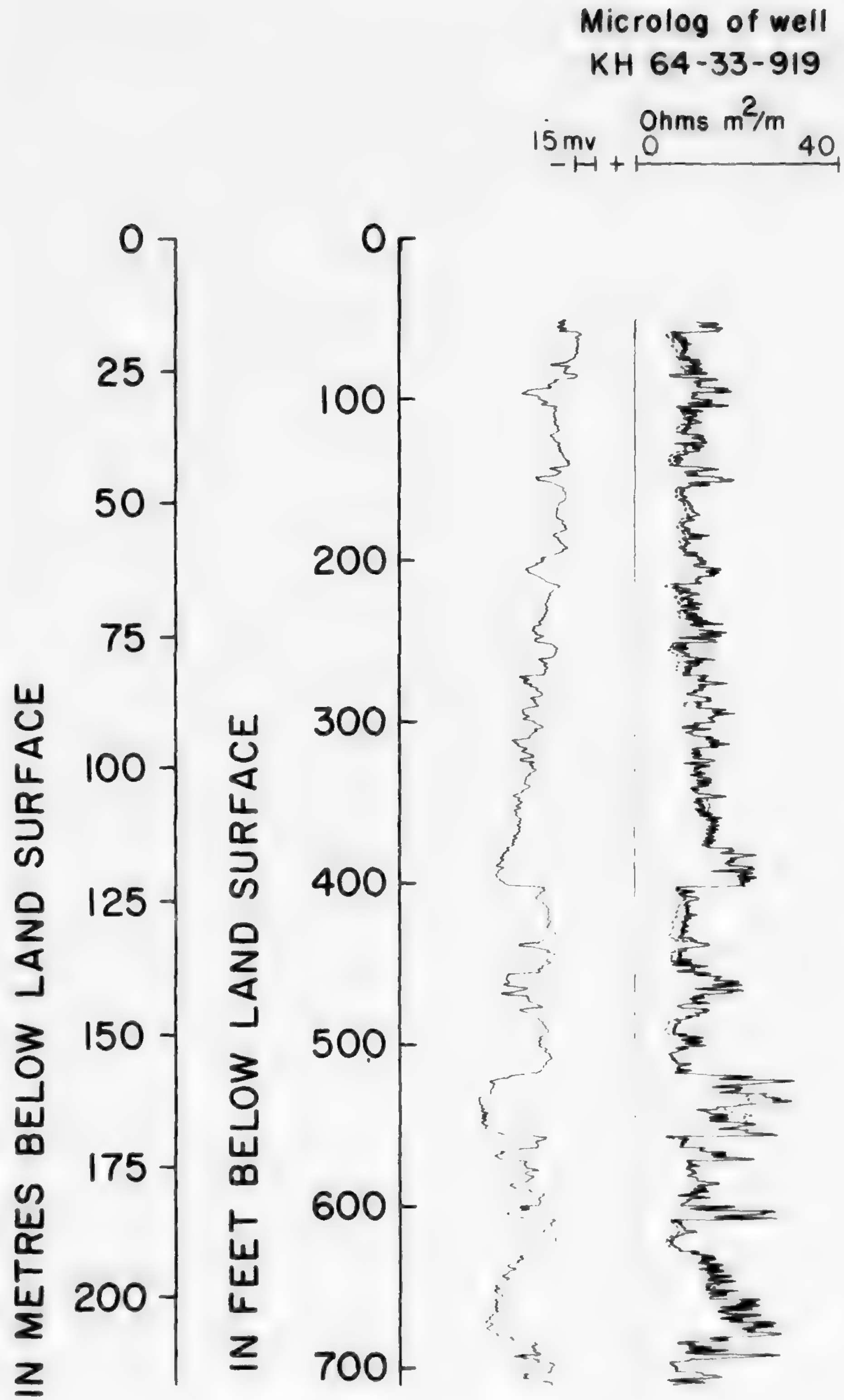

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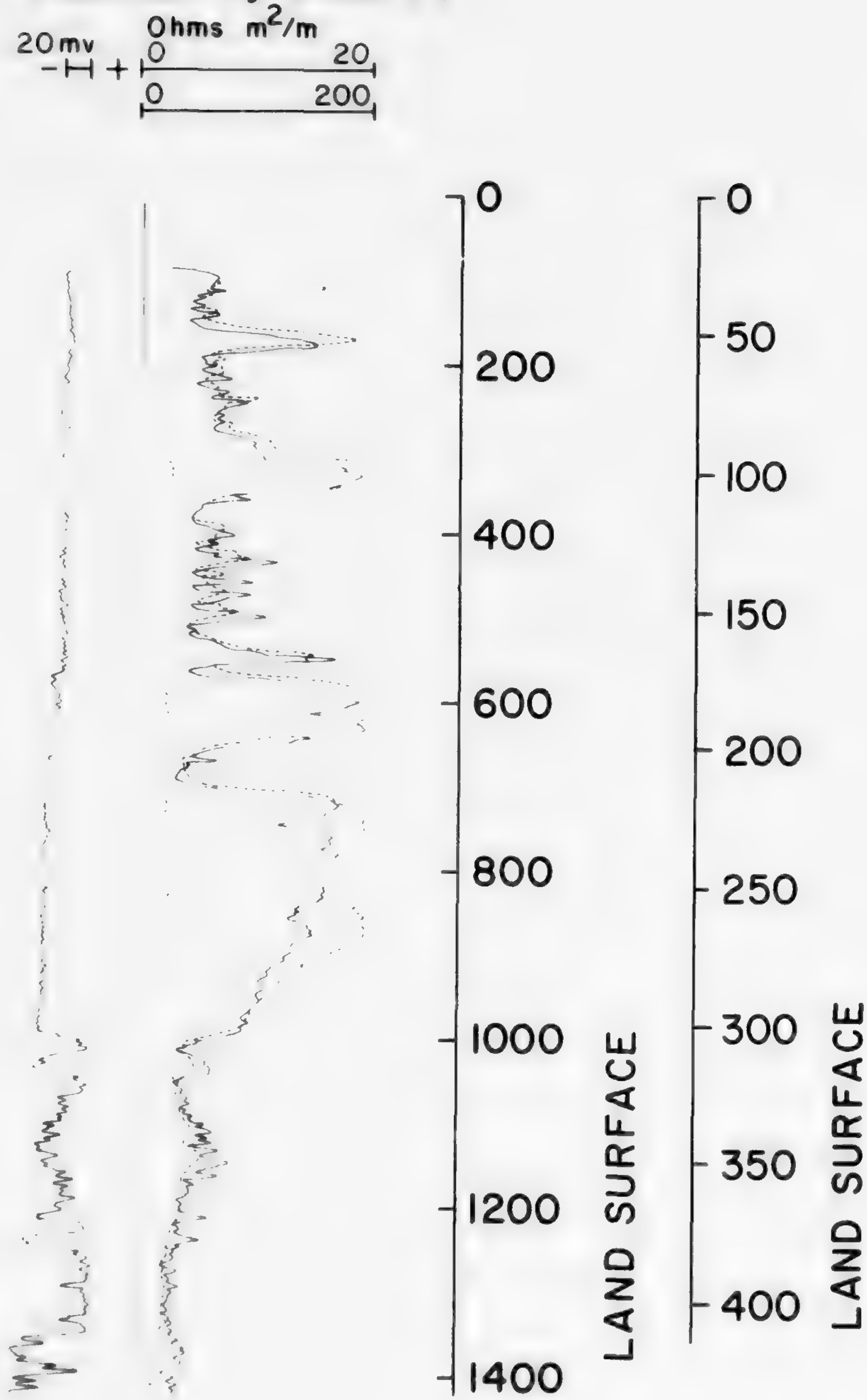
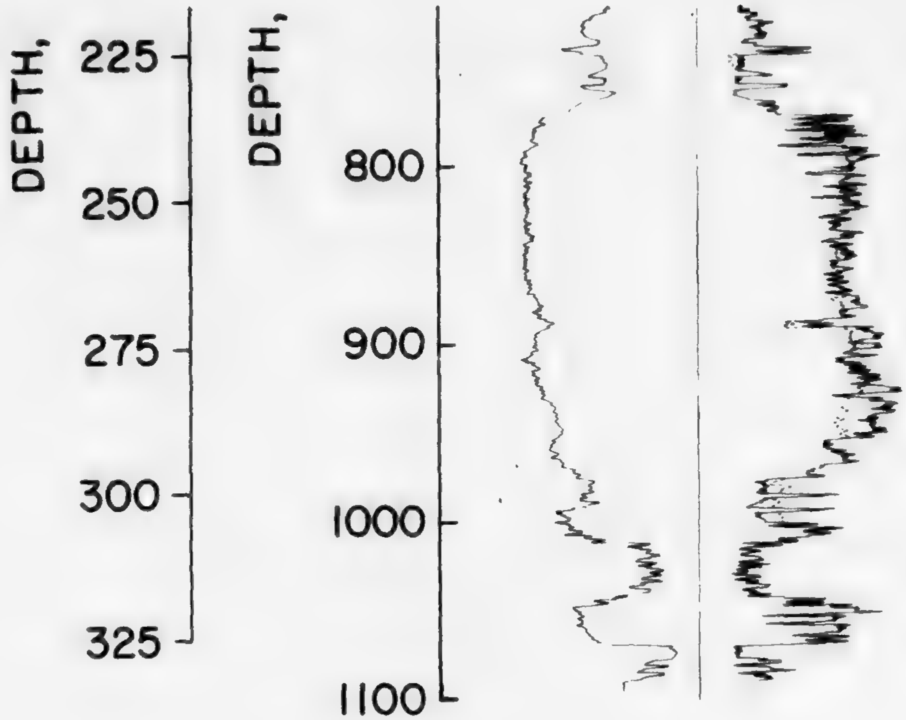
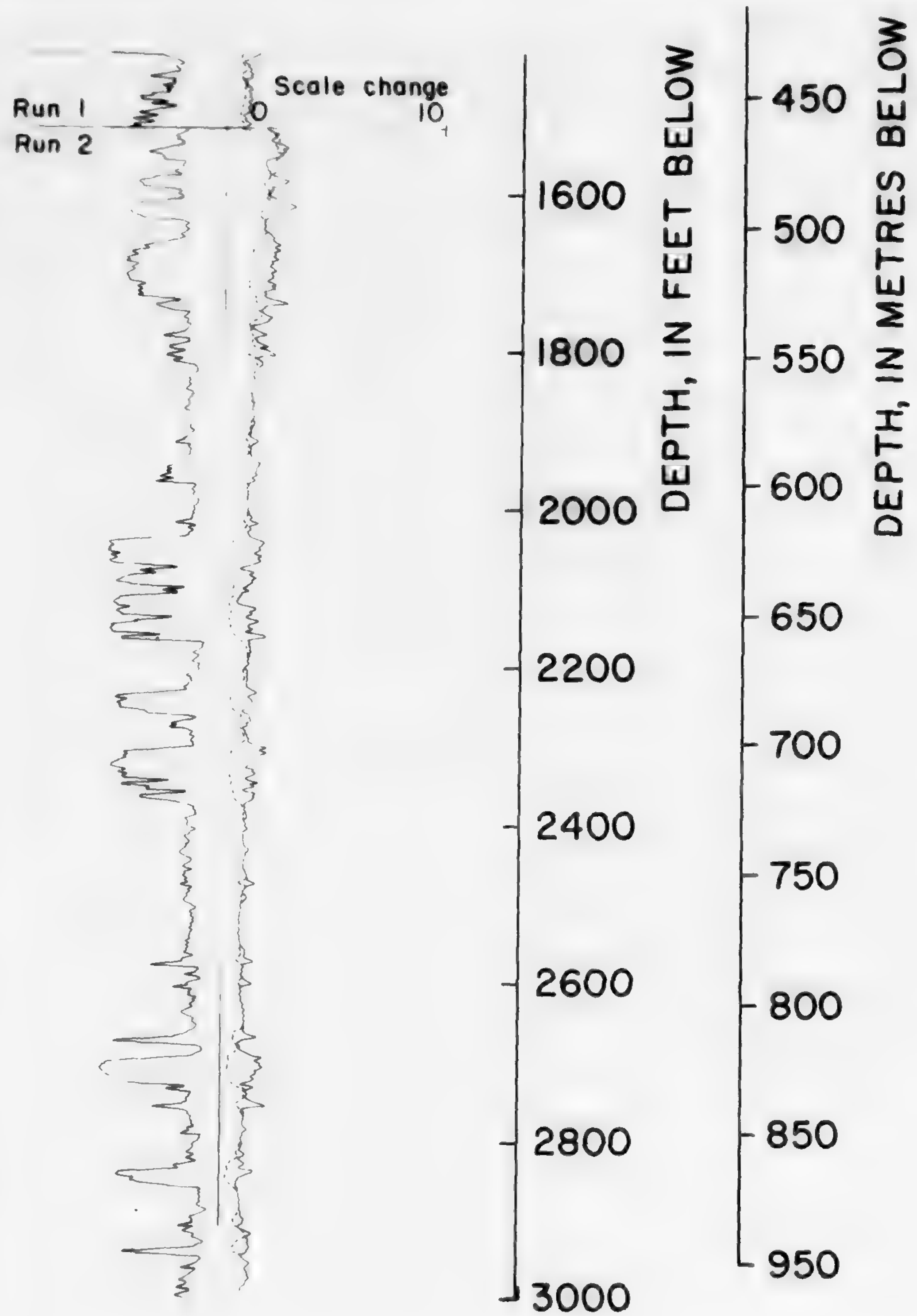
Electrical log of well F-2




DEPTH,
225
250
275
300
325
DEPTH,
800
900
1000
1100


Scale change
Run 1
0
10
Run 2
1600
1800
2000
2200
2400
2600
2800
3000
DEPTH, IN FEET BELOW
450
500
550
600
650
700
750
800
850
950
DEPTH, IN METRES BELOW

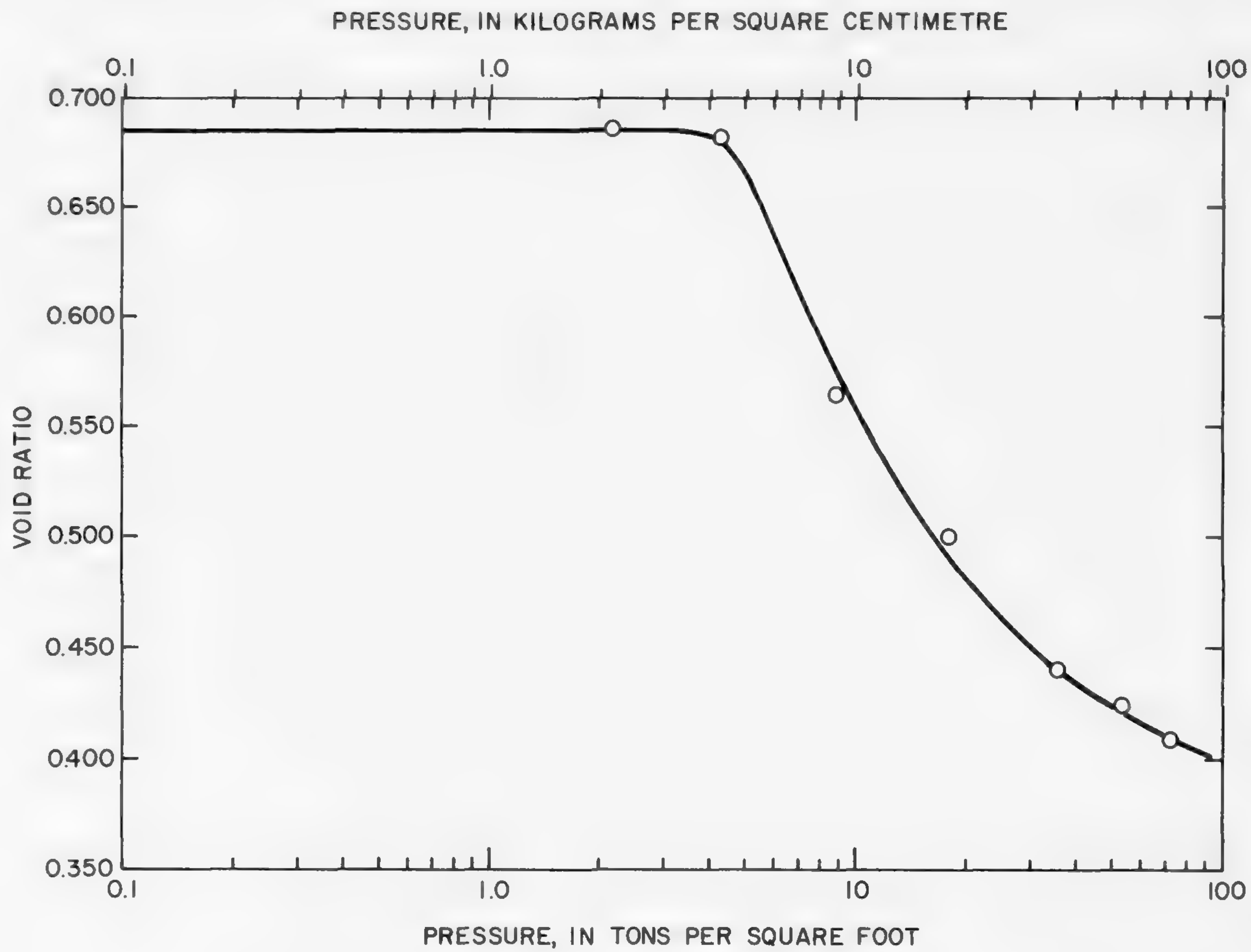


FIGURE 11.-Relation between void ratio and applied pressure for clay sample from a depth of 163 feet (50 m), well KH 64-33-920

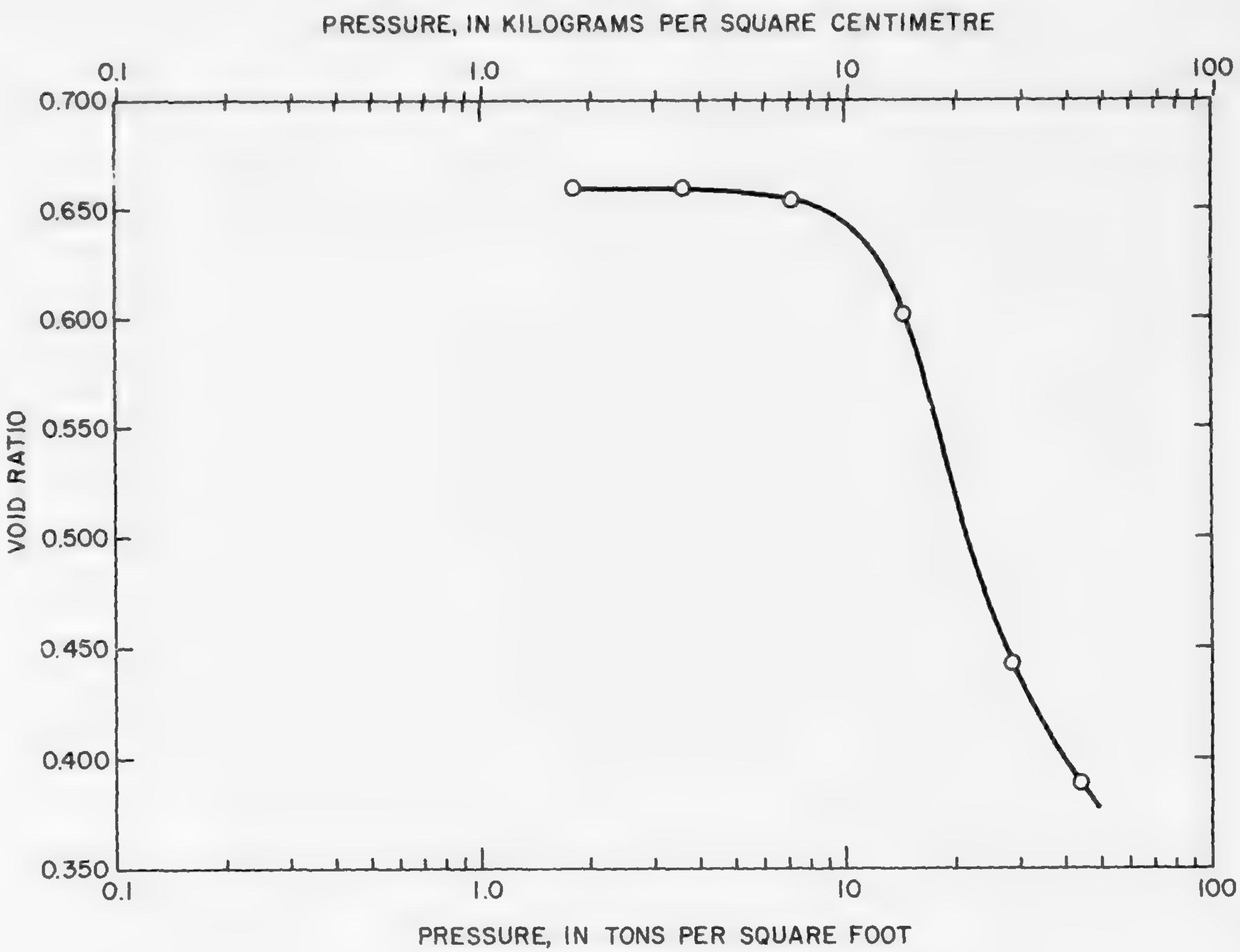


FIGURE 12.-Relation between void ratio and applied pressure for clay sample from a depth of 256 feet (78 m), well KH 64-33-920

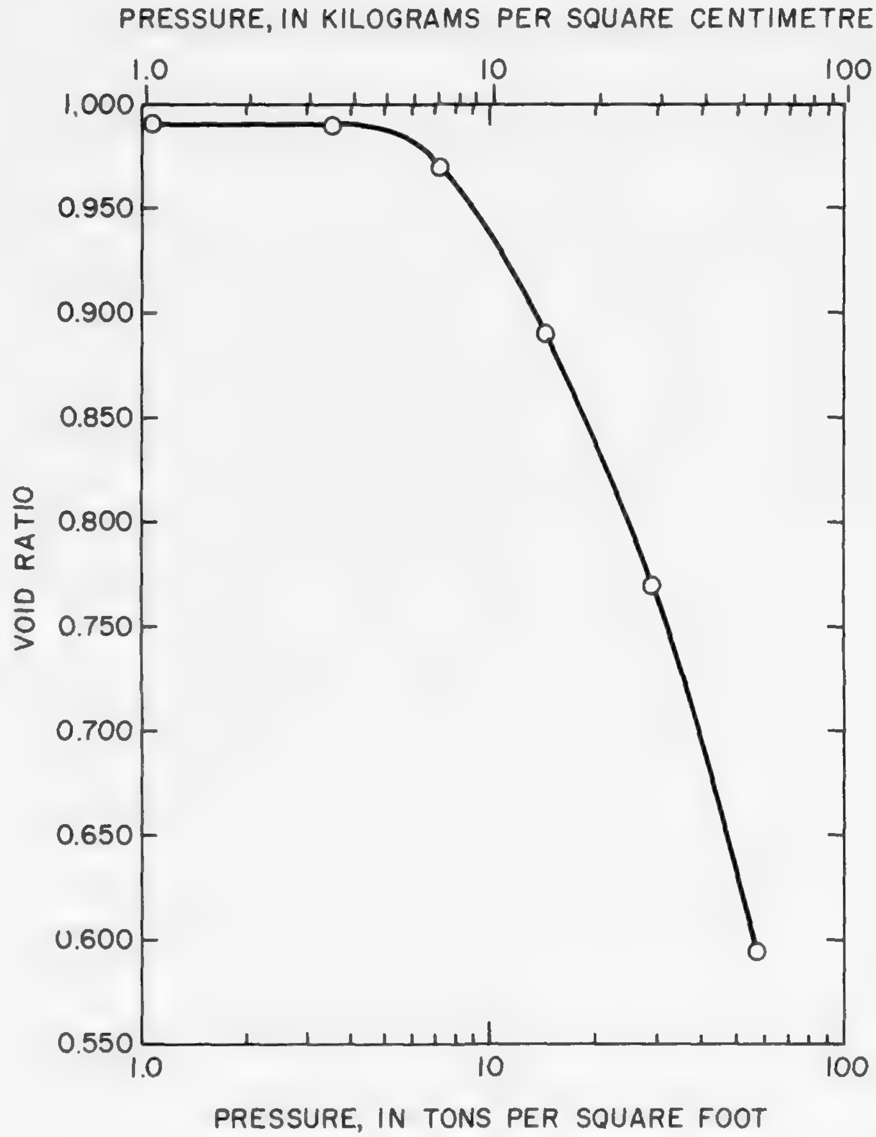


FIGURE 13.-Relation between void ratio and applied pressure for clay sample from a depth of 423 feet (129 m) , well KH 64-33-920

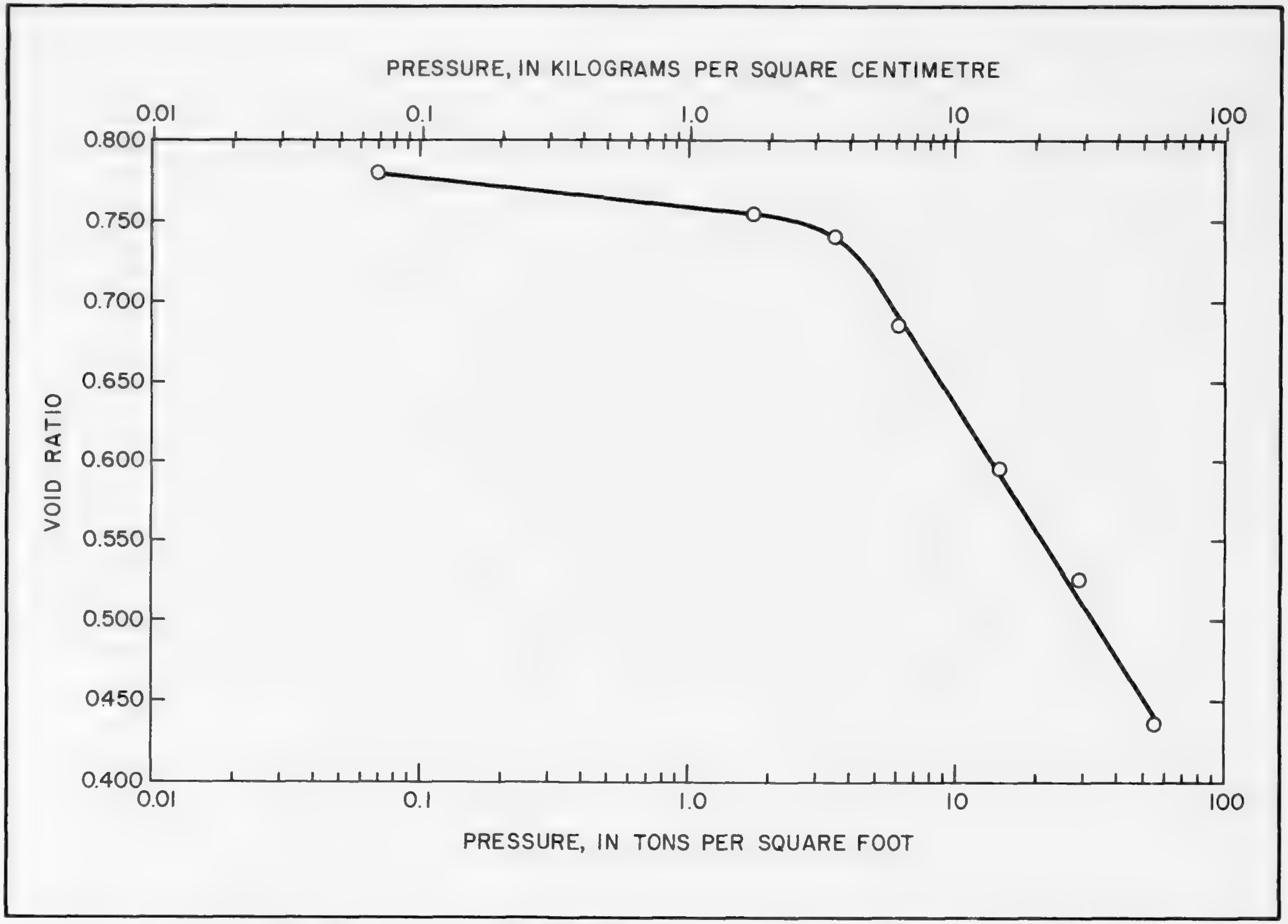


FIGURE 14.-Relation between void ratio and applied pressure for clay sample from a depth of 512 feet (156 m), well KH 64-33-920

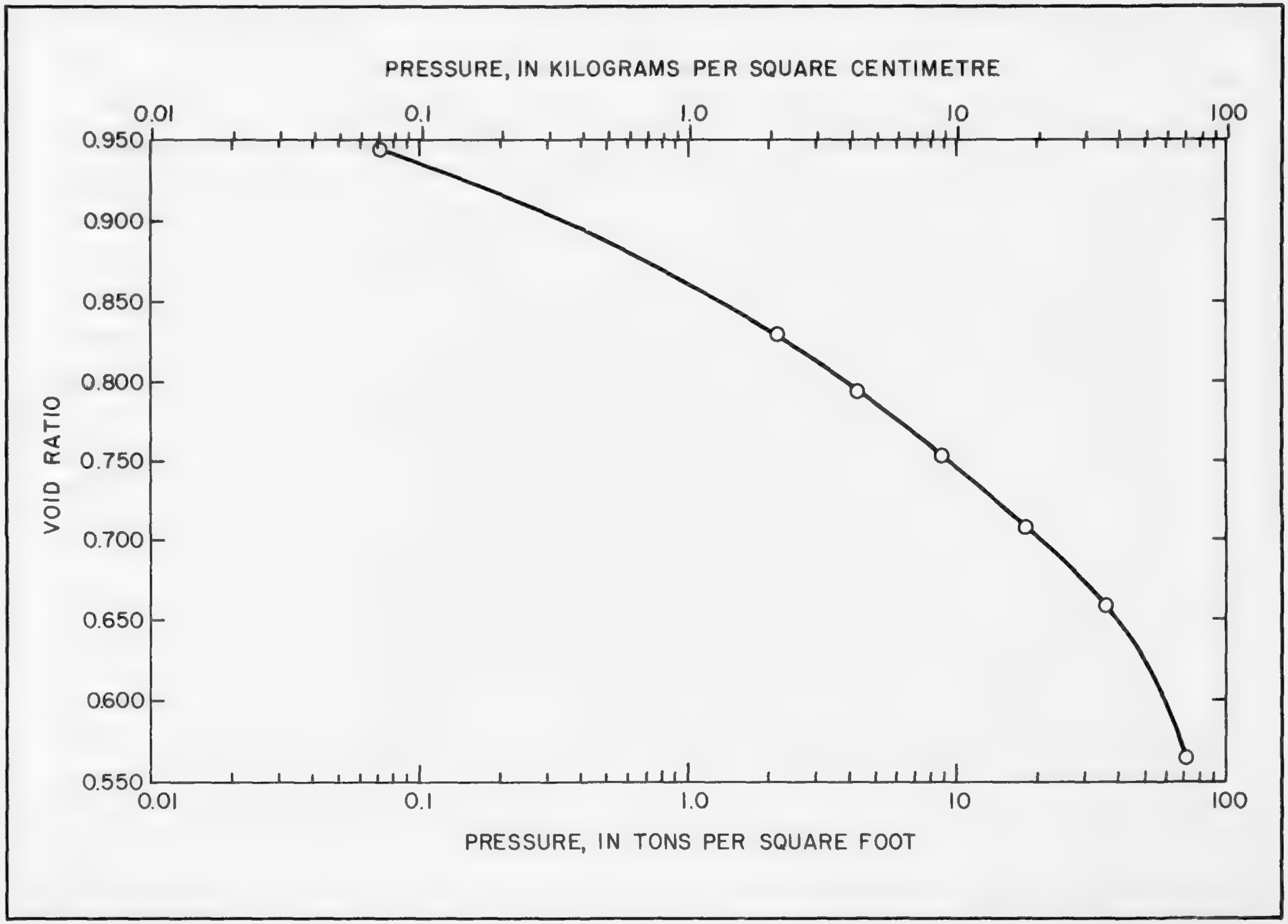


FIGURE 15.-Relation between void ratio and applied pressure for clay sample from a depth of 619 feet (189 m), well KH 64-33-920

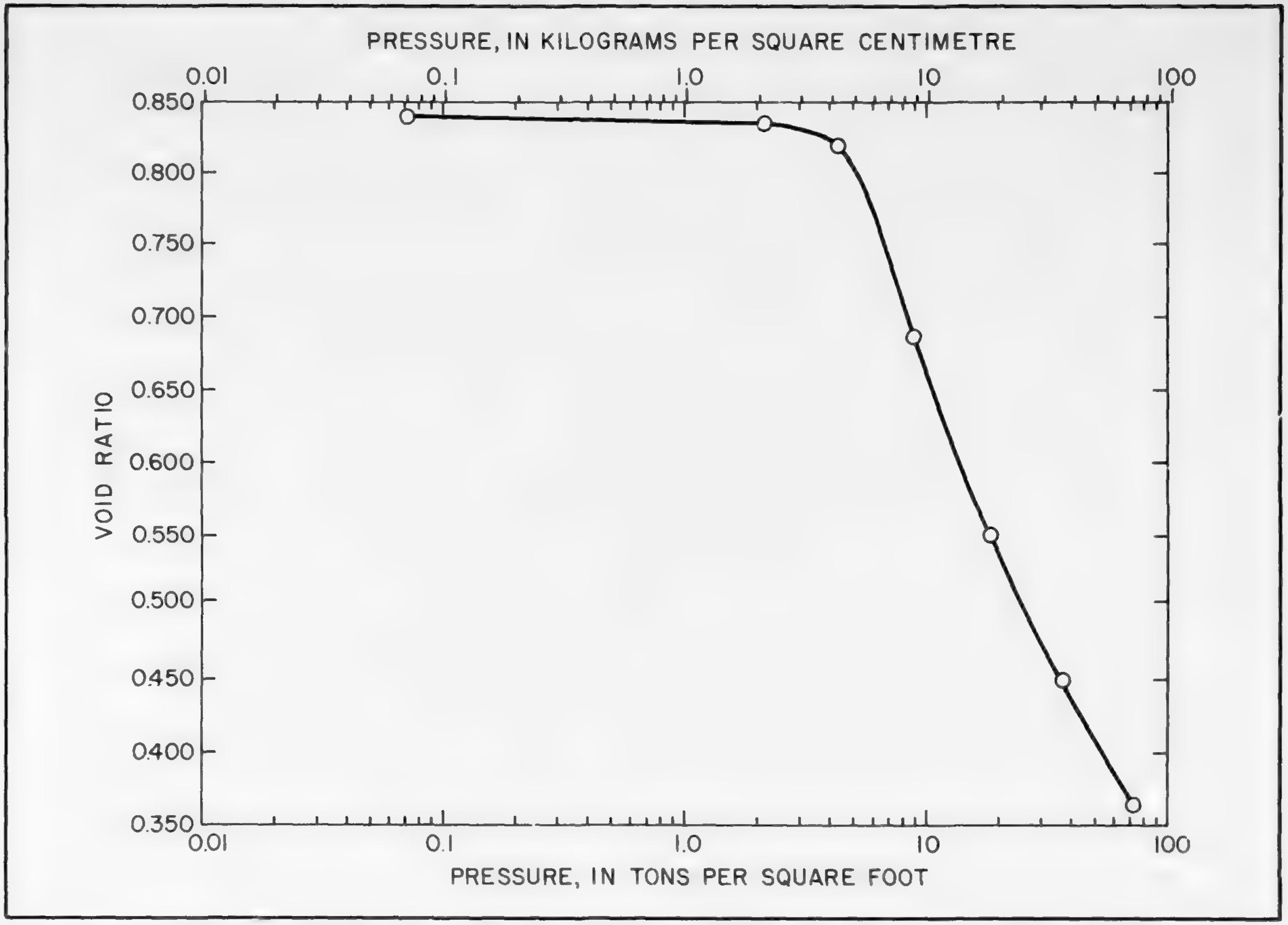


FIGURE 16.-Relation between void ratio and applied pressure for clay sample from a depth of 700 feet (213 m) , well KH 64-33-920

Measurements made in the observation wells were used to define the potentiometric profile and to estimate the loading in 1973. Published and unpublished maps showing gross approximations of the declines in artesian heads were used to estimate historical loading. However, hydrographs of individual wells or potentiometric maps based on either single or multi-screened wells are not totally descriptive of loading and compaction leading to subsidence. The wide variation in the altitude of potentiometric surfaces at different depths is shown on figure 17, which is a plot of measurements made in the observation wells.

The first method used to calculate subsidence was based on the Terzaghi theory of consolidation. The method is described in the report on Burnett, Scott, and Crystal Bays (Gabrysch and Bonnet, 1974a). Effective loads (stress) as derived from the analysis of data collected at the test site are shown on figure 18. At any given depth, the effective stress is the weight (per unit area) of sediments and moisture above the water table, plus the submerged weight (per unit area) of sediments between the water table and the specified depth, plus or minus the seepage stress (hydrodynamic drag) produced by downward or upward components, respectively, of water movement through the saturated sediments above the specified depth (Poland, Lofgren, and Riley, 1972, p. 6).

Subsidence calculated by use of the laboratory-determined characteristics and subsidence determined from maps of changes in elevations are shown on figure 19. The calculated amount far exceeded the actual amount of subsidence. In 1973, subsidence as based on calculations was 5.2 feet (1.6 m) as compared to measured subsidence of 1.8 feet (0.5 m). It is assumed that the clay samples tested did not represent the materials being compacted.

The second method used and the one adopted for prediction is based on historic changes in stress (mean changes in artesian head) and the specific unit compaction determined from field data. The specific unit compaction is defined as the unit of compaction per unit clay thickness per unit stress change during a specific time period.

The following assumptions were used to predict the rate of subsidence and the maximum amount of subsidence.

1. The altitude of the potentiometric surface in 1900 was the original surface and no subsidence occurred before 1900. On the basis of elevations determined by the United States Coast and Geodetic Survey and U.S. Geological Survey, the land surface subsided about 0.4 foot (0.122 m) between 1906 and 1943 (Gabrysch and Bonnet, 1974b, fig. 10, p. 17).
2. Artesian-head declines in the middle part of the Chicot aquifer, the Alta Loma Sand, and Evangeline aquifer will continue at rates of 1.0, 3.0, and 3.0 feet (0.3, 0.9, and 0.9 m) per year, respectively, until 1980. Thereafter, no further head declines will occur (case I).
3. Artesian-head declines in the middle part of the Chicot aquifer, the Alta Loma Sand, and Evangeline aquifer will continue at rates of 1.0, 3.0, and 3.0 feet (0.3, 0.9, and 0.9 m) per year, respectively, until 1990. Thereafter, no further head declines will occur (case II).

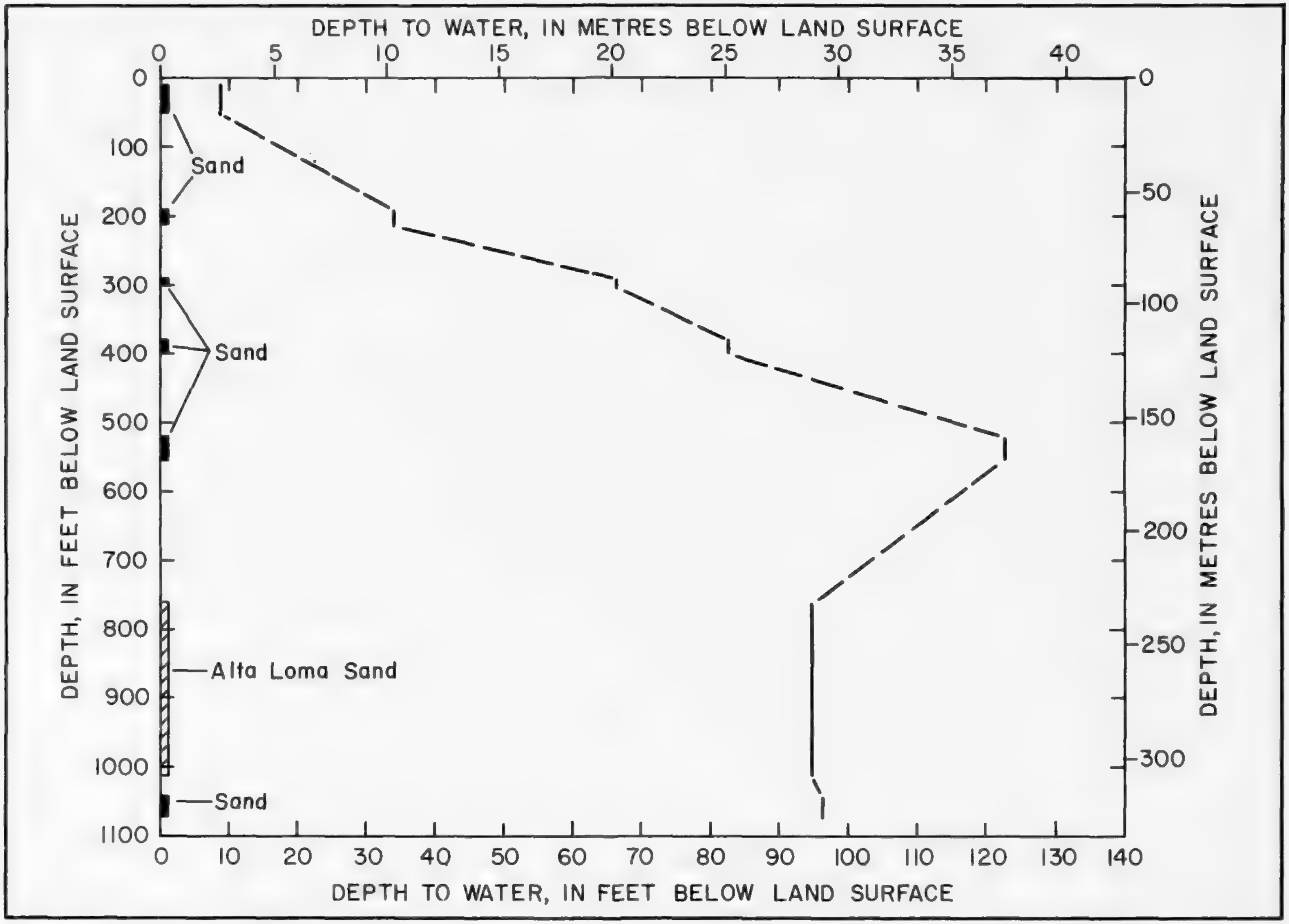
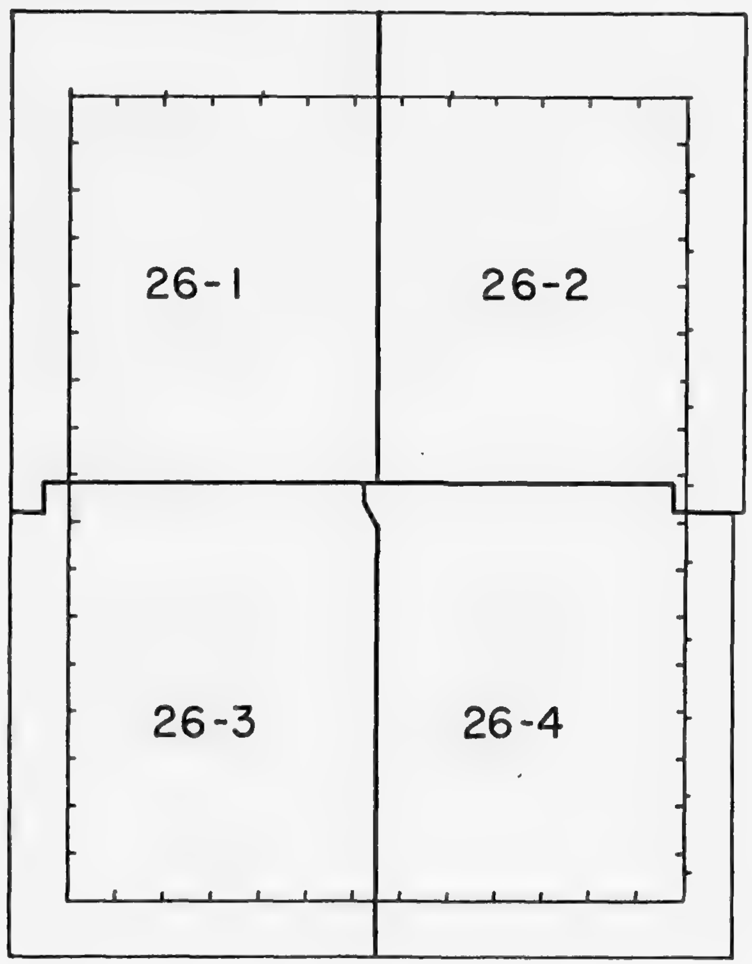


FIGURE 17.-Potentiometric profile at Moses Lake, August 1974

FIGURE 18

EFFECTIVE LOAD AT DEPTHS BETWEEN 0 AND 1650 FEET (0 AND 503 M) AT MOSES LAKE



Index diagram showing page numbers of each component of figure 18

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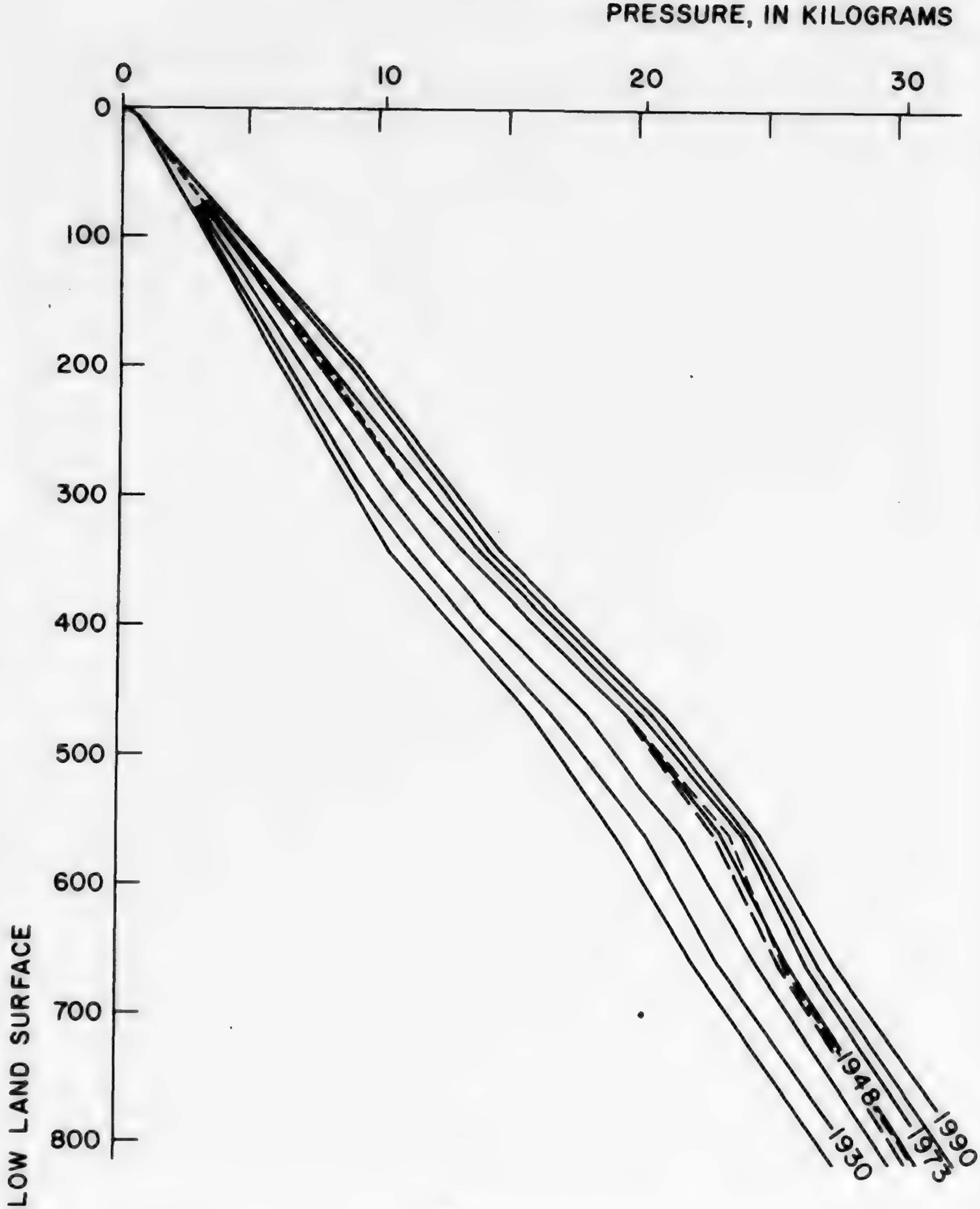

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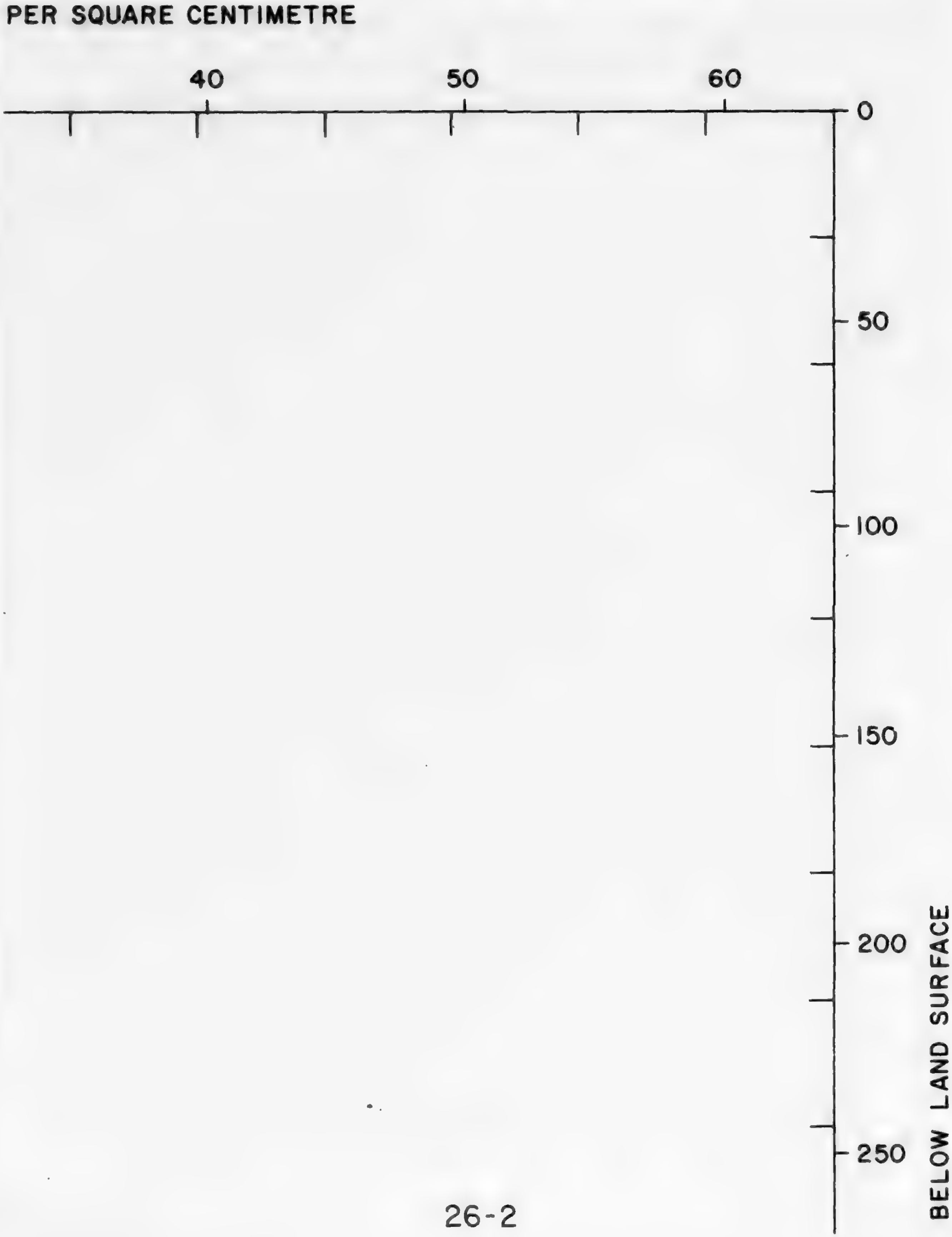

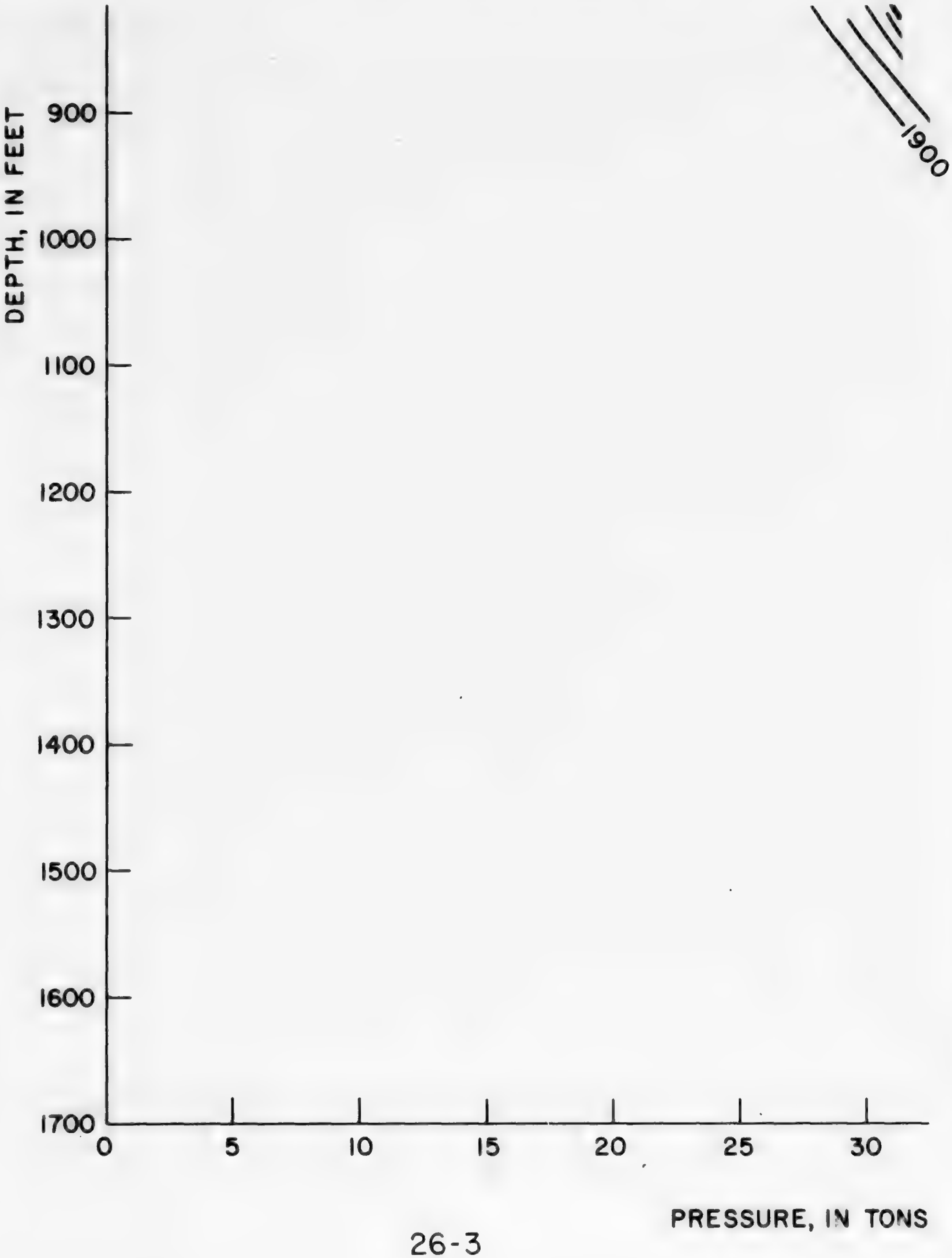
DEPTH, IN FEET
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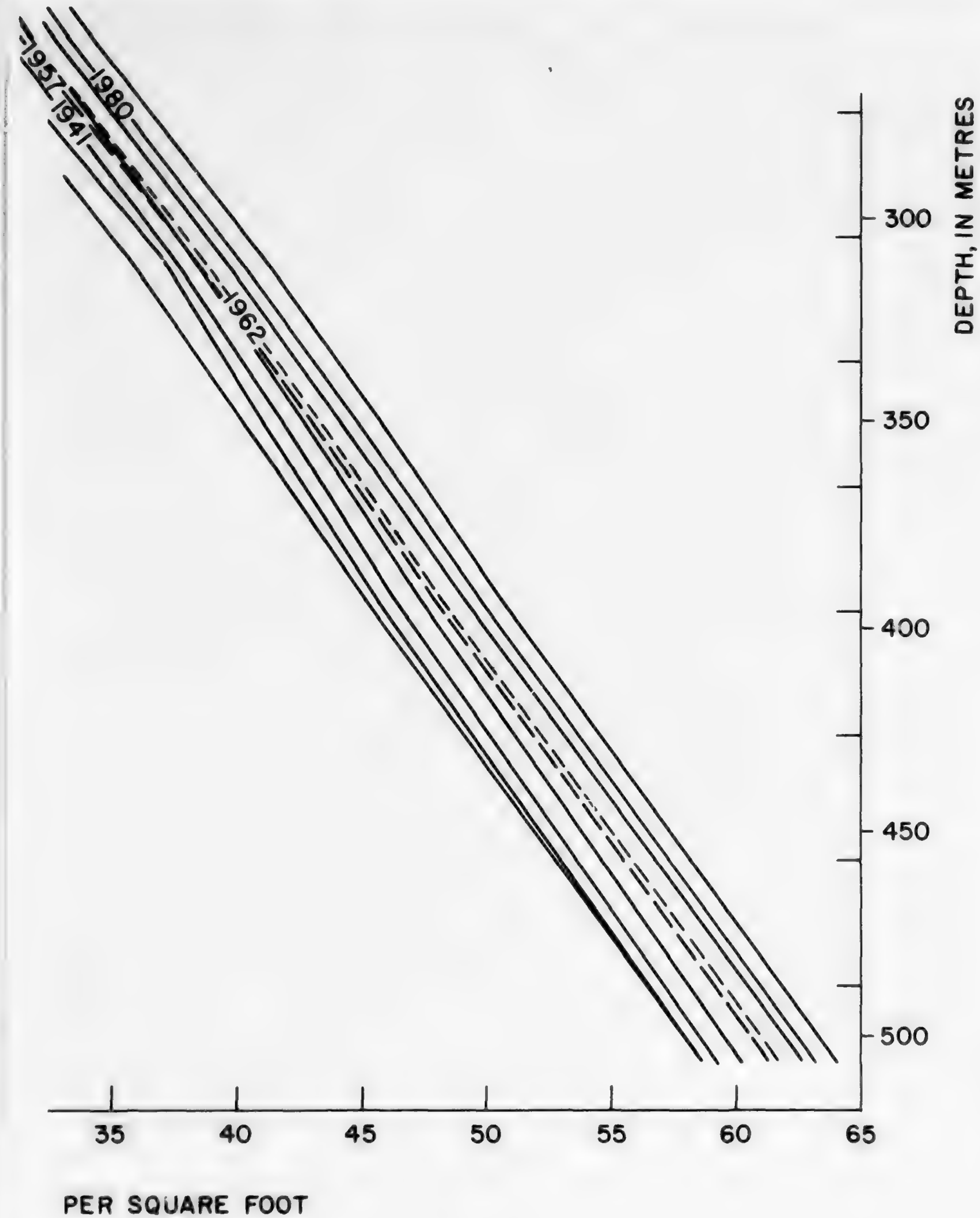
1000
1100
1200
1300
1400
1500
1600
1700
0
5
10
15
20
25
30
PRESSURE, IN TONS
1900


1980
1957
1941
1962
DEPTH, IN METRES
300
350
400
450
500
35
40
45
50
55
60
65
PER SQUARE FOOT

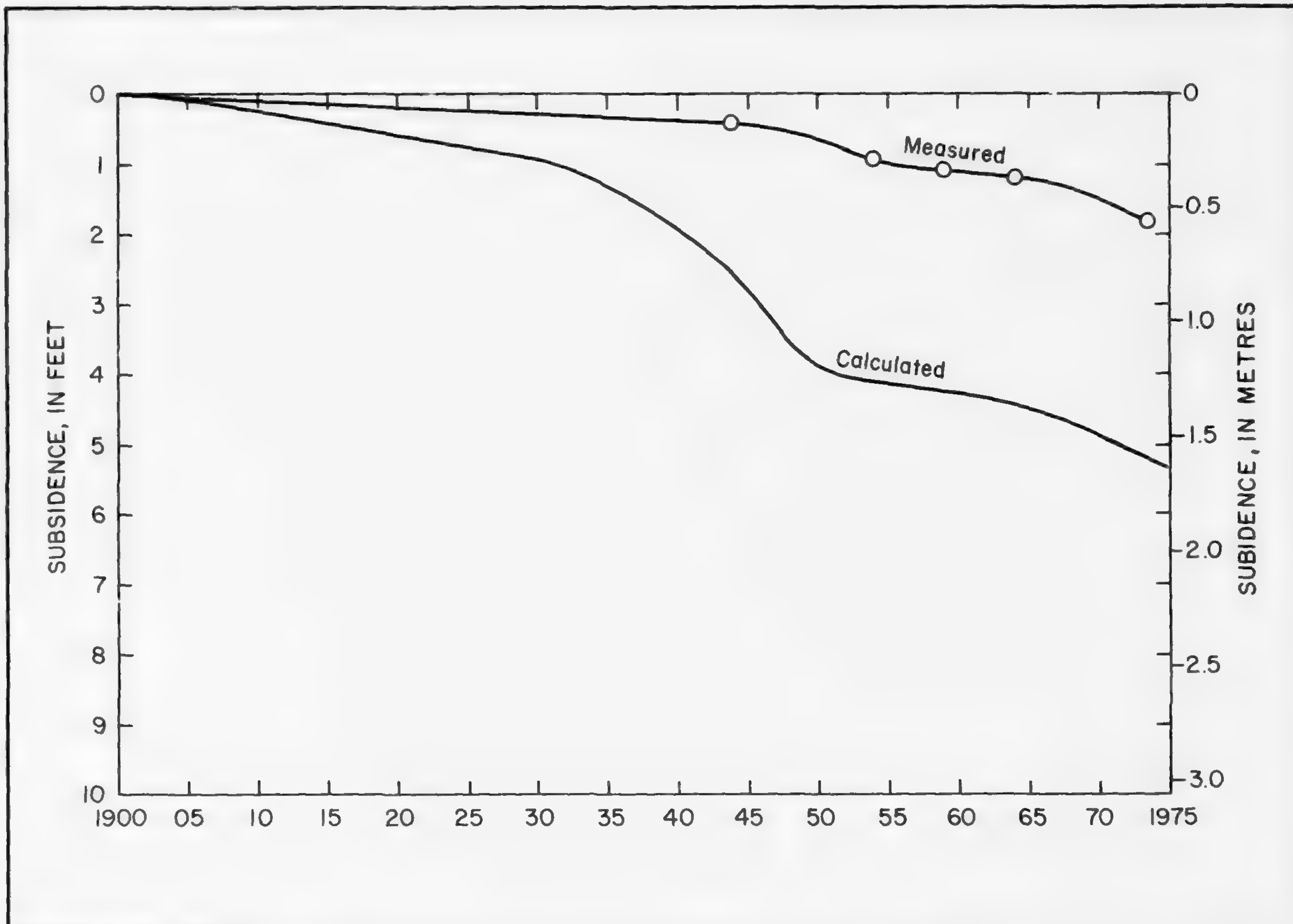


FIGURE 19.-Measured and calculated land-surface subsidence, 1900-75

Subsidence and change of stress have been determined for 1906-43, 1945-53, 1954-58, 1959-63, and 1964-73. Figure 20 shows the change in stress, as decline in artesian head, that occurred at the test site and the assumed change in stress used for prediction. Figure 20 shows that most of the artesian-head decline occurred in the sand and gravel beds above the Alta Loma Sand. The diagram shows as much as 150 feet (45.7 m) of head decline since 1900. The change in head results in loading of the most compressible layers of the entire section.

Specific unit compaction for each of the individual periods was calculated on the basis of the average change in stress, a total clay thickness of 497 feet (151.5 m) at the test site, and measured subsidence. In addition, the specific unit compaction for two periods that included some of the individual periods was calculated. The calculated values, tabulated in the following table for the periods of subsidence, ranged from 1.1×10^{-5} to 9.91×10^{-5} ft^{-1} (3.6×10^{-5} to 3.25×10^{-4} m^{-1}). The lower value, which was obtained for the earliest period, represents recompression and, at least in part, the elastic properties of the system. The highest value was obtained for 1943-58, when some recovery of water levels (unloading) occurred. The average stress change used for prediction was the stress change for the most recent period, 1964-73, because it is a measure of the current rate of loading. For the same reason, a value for specific unit compaction of 6.46×10^{-5} ft^{-1} (2.13×10^{-4} m^{-1}) was used for computing subsidence until 1980 and 1990 under the assumed conditions.

Period	Average stress change (feet of water)	Subsidence (feet)	Specific unit compaction (ft^{-1})
1906-43	72.9	0.4	1.1×10^{-5}
1943-53	13.5	.5	7.2×10^{-5}
1954-58	1/ .3	.15	--
1959-63	7.6	.15	3.97×10^{-5}
1964-73	18.7	.6	6.46×10^{-5}
1943-58	13.2	.65	9.91×10^{-5}
1943-73	38.2	1.4	7.37×10^{-5}

1/ Decrease in average stress (rise in water levels).

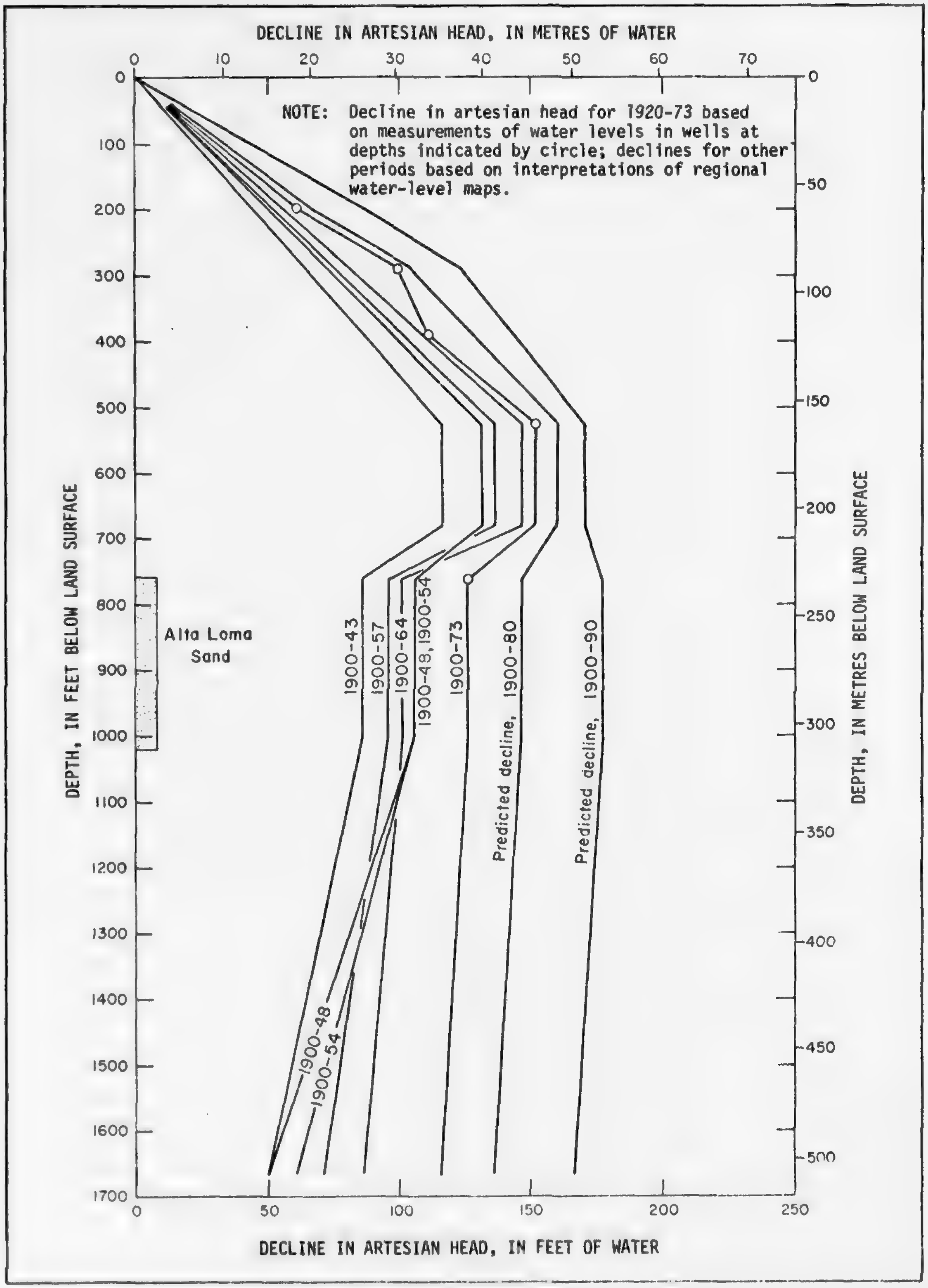


FIGURE 20.-Approximate decline in artesian head

The specific storage (defined as the volume of water released from a unit volume of a saturated medium as a result of a unit decline in head) is a measure of ultimate specific compaction. The specific storage of the clay samples from the Moses Lake site ranged from 5.4×10^{-5} to 4.9×10^{-4} ft^{-1} (1.77×10^{-4} to 1.61×10^{-3} m^{-1}). The weighted average of the values determined by laboratory tests of six cores from the Moses Lake site (and four cores from a site at Seabrook) was 1.4×10^{-4} ft^{-1} (4.59×10^{-4} m^{-1}). The values were weighted according to the thickness of clay to which each applies.

The laboratory value for specific storage (1.4×10^{-4} ft^{-1} or 4.59×10^{-4} m^{-1}) appears high in comparison to the field data. The maximum value derived from field data (subsidence per unit thickness of clay per unit decline in artesian head) was 9.91×10^{-5} ft^{-1} (3.25×10^{-4} m^{-1}) for a period in which a small amount of unloading occurred. However, some subsidence was still occurring, and the specific unit compaction should exceed 9.91×10^{-5} ft^{-1} (3.25×10^{-4} m^{-1}). To compute ultimate subsidence due to loads from 1973 to 1980 and 1980 to 1990, a minimum value of specific unit compaction of 1.0×10^{-4} ft^{-1} (3.28×10^{-4} m^{-1}) and a maximum value of 1.2×10^{-4} ft^{-1} (3.93×10^{-4} m^{-1}) were used.

The calculated ultimate subsidence in the Burnett, Scott, and Crystal Bays area near Baytown, Texas, due to water-level decline by 1973 was 9.6 feet (2.9 m). By 1973, 8.2 feet (2.5 m) of subsidence had occurred suggesting a residual of 1.4 feet (0.4 m) or about 15 percent of ultimate subsidence (Gabrysch and Bonnet, 1974a). It was conservatively assumed at Moses Lake that 80 percent of the expected subsidence due to hydrodynamic compaction caused by artesian-head declines to date has already occurred. Thus, 20 percent additional subsidence might be expected as a result of artesian-head declines that occurred before 1973. It is estimated that 1.8 feet (0.55 m) of subsidence has occurred at Moses Lake and that additional subsidence of about 0.5 foot (0.152 m) would occur because of artesian-head declines before 1973.

The subsidence that could be expected in the two assumed cases of artesian-head decline is shown on figure 21. The range in subsidence for each case includes the maximum and minimum that could be expected. Under the conditions of case I, the maximum and minimum ultimate subsidence to be expected is 3.3 feet (1.0 m) and 3.0 feet (0.9 m); under the conditions of case II, the maximum and minimum ultimate subsidence to be expected is 4.6 feet (1.4 m) and 3.9 feet (1.2 m). Because of the complexity of the system and the many assumptions that must be made, it should be stressed that the predicted subsidence is at best an approximation.

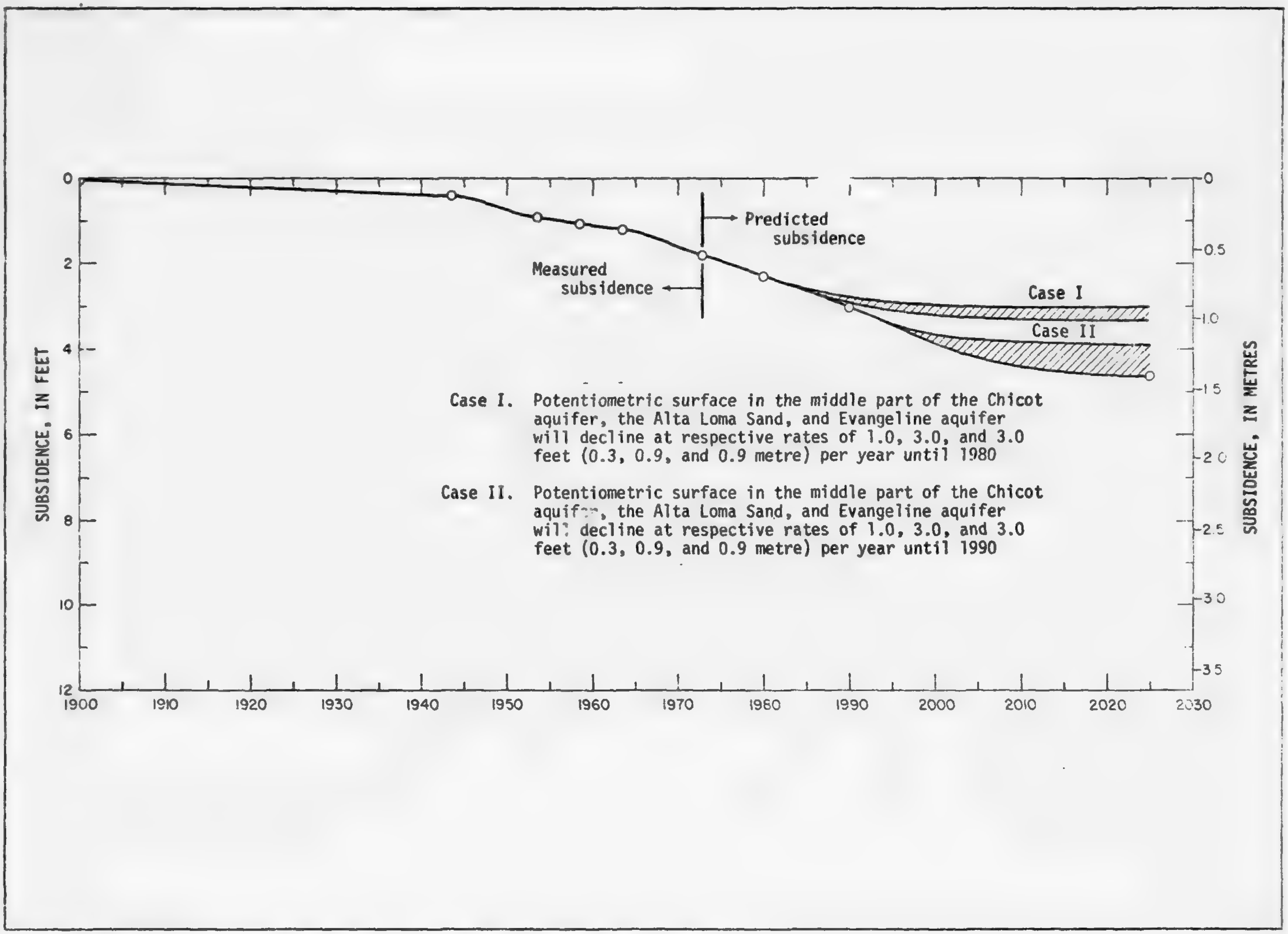


FIGURE 21.-Measured and predicted subsidence at Moses Lake, 1900-2025

CORRECTIVE MEASURES

Subsidence of the land surface in the Moses Lake area will continue until pore pressures in the clay beds reach equilibrium with the pressures in the adjacent sand beds. Therefore, even if artesian heads in the aquifers are maintained at 1973 levels, compaction of the clay layers would continue, but at a decreasing rate. To halt compaction, the artesian head in the sand beds needs to be raised to a value equal to the pore pressure in the adjacent clay beds. Data on the excess pore pressure in the clays have not been collected at Moses Lake, but the data collected at Baytown indicate that the necessary recovery of artesian head may be as much as 135 feet (41.1 m) or 58 lb/in^2 (4.08 kg/cm^2). However, malfunction of the pore-pressure measuring device leaves doubt as to the validity of this head difference. Experience at Texas City showed that with a small amount of average net recovery of water levels (less than 1 foot or 0.3 m) the rate of subsidence decreased markedly.

The artesian head may be raised by decreasing the rate of ground-water pumping or by artificially recharging the aquifer. Artificial recharge would require that the injected water be of a quality suitable for future use and be compatible with the native ground water and associated water-bearing material. Any available surface water would have to be treated before injection.

Although at least a dozen wells drilled for the disposal of liquid wastes are in operation in Harris and surrounding counties, no large-scale fresh-water injection is underway or planned. Additional fresh water is available to Harris and Galveston Counties from both ground-water and surface-water sources along the Gulf Coast. A decrease in pumping would allow artesian heads to increase by natural means and is probably the most logical solution to the problem of artesian-head declines and land-surface subsidence.

PLANNED DEVELOPMENT AND SUBSIDENCE

Pumping of ground water in the Houston-Galveston region has continued to increase, and the rates of artesian-head decline and subsidence have accelerated. Subsidence will continue at a rate dependent on the decline in head resulting from ground-water pumping. Commitments for future use of about 166 million gal/d (7.3 m^3/s) of surface water from Lake Livingston have been received from 24 major ground-water users in the southern part of Harris County. In addition, several minor ground-water users have recently begun to use surface water or firmly plan to do so. Texas City and La Marque are planning to use water from the Brazos River.

The increased use of surface water would reduce pumpage of ground water and would probably result in some recovery of artesian head. The city of Galveston began using surface water in August 1973 and has decreased ground-water withdrawals by about 6 million gal/d (0.3 m^3/s). Water levels in some wells in the Alta Loma area were about 15 feet (4.6 m) higher in February 1974 than in February 1973.

The actual or planned decrease in withdrawals of ground water was programed in an analog model (Jorgensen, 1974) of the ground-water system of the Houston-Galveston region. Results of the model study (Jorgensen and Gabrysch, 1974) indicate a rapid rise in artesian heads in the southern part of Harris County. Within a few months, as much as 35 feet (10.7 m) of recovery might be expected in parts of the potentiometric surface of the Chicot aquifer, and 20 feet (6.1 m) of recovery could be expected in the potentiometric surface of the Evangeline aquifer at Seabrook. In the Texas City area, the indicated recoveries in artesian head by 1980 would be about 50 feet (15 m) in the Alta Loma Sand and about 20 feet (6 m) in the Evangeline aquifer. With recovery of artesian head in southern Harris and northern Galveston Counties, the rate of subsidence should decrease substantially in the Moses Lake area. However, unless increasing demands for water are met from surface-water sources (or remote ground-water sources), the recovery would be short-lived, and subsidence would resume.

SUMMARY AND CONCLUSIONS

The pumping of ground water in Harris and Galveston Counties, Texas, has caused a decline in artesian head at Moses Lake of as much as 145 feet (44 m), which in turn has caused subsidence of the land surface. Subsidence at Texas City began in the late 1930's, and by 1943 as much as 1.6 feet (0.49 m) had occurred in the industrial area. During 1943-52, the rates of subsidence at four bench marks in the industrial area ranged from 0.213 to 0.336 foot per year (0.065 to 0.102 m).

The rates of subsidence decreased after 1948 because of recovery of artesian heads associated with a decrease in ground-water pumping. In each of the two 5-year periods, 1954-58 and 1959-63, the average rate of subsidence was 0.04 to 0.06 foot (0.012 to 0.018 m) per year. Since 1964, the rate of subsidence increased to about 0.11 foot (0.034 m) per year.

The Moses Lake area is about 4 miles (6.4 km) north of the central part of the industrial area of Texas City, but subsidence at Moses Lake has been much less than in the industrial area. About 0.4 foot (0.122 m) of subsidence occurred before 1943, and 1.4 feet (0.43 m) of subsidence occurred between 1943 and 1973.

Seven wells were drilled at the test site at Moses Lake to collect data on the properties of the clays and on artesian heads in the sands. One well was completed as a borehole extensometer to monitor compaction of material between land surface and a depth of 800 feet (244 m). Most of the subsidence at Moses Lake is probably due to compaction of material above the Alta Loma Sand; therefore, the extensometer record should be valuable for estimating subsidence on a continuing basis.

Six clay cores obtained from one well drilled at Moses Lake were tested to determine compressibility characteristics. These data, together with compressibility data on cores from other sites, were used to compute subsidence by the Terzaghi theory of consolidation. The subsidence computed by this method far exceeded the measured subsidence experienced; therefore, the amount of subsidence was determined on the basis of historic changes in stress (mean change in artesian head) and the specific unit compaction as determined from field data.

To predict future subsidence, it was assumed that water levels would decline at the 1973 rate until 1980 (case I) and until 1990 (case II). The predicted mean change in stress was applied to the specific unit compaction to calculate subsidence through the period of artesian-head decline. The specific storage as determined in the laboratory and the specific unit compaction were used to estimate the ultimate subsidence that would result from the declines in artesian heads between 1973 and 1980 and between 1973 and 1990.

Bench-mark data indicated that 1.8 feet of subsidence had occurred at Moses Lake. On the basis of calculations at Baytown, the expected residual subsidence due to artesian-head decline before 1973 was conservatively estimated to be 0.5 foot (0.152 m) or 20 percent of total subsidence. Under the conditions of case I, the minimum and maximum ultimate subsidence to be expected is 3.0 feet (0.9 m) and 3.3 feet (1.0 m); under the conditions of case II, the minimum and maximum ultimate subsidence to be expected is 3.9 feet (1.2 m) and 4.6 feet (1.4 m). Because of the complexity of the system and the many assumptions that must be made, the predicted amounts of subsidence should be considered as approximations.

Water from Lake Livingston will be available in the Houston-Galveston area in 1976. Planned use of the surface water will allow a decrease in ground-water pumping and a recovery of artesian head of about 50 feet in the Chicot aquifer and 20 feet in the Evangeline aquifer. As a result of the recovery, the rate of subsidence should decrease substantially in the Moses Lake area.

Table 1.--Clay minerals in samples from Texas and California

Site	Number of samples	Clay minerals (percent)			
		Montmorillonite	Illite	Chlorite and kaolinite-type minerals	Mixed layer clay minerals
Seabrook 1/	5	21	21	9	49
JSC 2/	8	65	15	20	--
Baytown 1/	4	40	10	24	26
Texas City 1/	6	26	20	14	40
California 3/	85	70	10	15	5

1/ Analysis by U.S. Geological Survey Hydrologic laboratory.
2/ Johnson Space Center, analysis by Corliss and Meade (1964).
3/ Los Banos-Kettleman City area - analysis reported by Meade (1967).

Table 2.--Physical properties of clay samples

Sample no 1/	Sample depth (feet)	Specific gravity	Water content (percent)	Liquid limit (percent)	Plastic limit (percent)
1	163	2.63	19	40	18
2	256	2.67	21	78	30
3	423	2.66	32	56	27
4	512	2.72	26	51	25
5	619	2.69	32	78	33
6	700	2.71	14	47	21
7	979	2.66	18	30	14
8	1,059	2.70	18	30	13
9	1,250	2.71	23	47	20
10	1,340	2.69	16	37	15

1/ Samples 1-6 from Moses Lake site; samples 7-10 from Seabrook site. All samples tested by U.S. Geological Survey laboratory, Denver, Colorado.

Table 3.--Coefficients of consolidation and hydraulic conductivities of clay samples

Sample no. 1/	Depth (feet)	Time - consolidation data		
		Load (ton/ft^2)	Coefficient of consolidation, c_v (cm^2/s)	Hydraulic conductivity, k (cm/s)
1	163	5.8	7.0×10^{-5}	1.1×10^{-9}
2	256	9.8	5.0×10^{-4}	2.0×10^{-9}
3	423	15.4	5.3×10^{-4}	2.4×10^{-9}
4	512	19.5	2.4×10^{-4}	8.1×10^{-10}
5	619	22.0	1.8×10^{-4}	3.2×10^{-10}
6	700	24.6	5.6×10^{-5}	2.0×10^{-10}
7	979	36.5	1.8×10^{-4}	2.4×10^{-10}
8	1,059	37.9	8.0×10^{-4}	6.4×10^{-10}
9	1,250	44.0	1.1×10^{-4}	4.2×10^{-10}
10	1,340	46.8	3.2×10^{-4}	2.7×10^{-10}

1/ Samples 1-6 from Moses Lake site; samples 7-10 from Seabrook site. All samples tested by U.S. Geological Survey laboratory, Denver, Colorado.

Table 4.--Thickness of clay and maximum clay-bed thickness

Layer number	Depth interval (feet)	Clay thickness1/ (feet)	Maximum clay-bed thickness (feet)
1	58-76	18	18
2	84-86	2	2
3	96-100	4	4
4	108-122	14	14
5	134-142	8	8
6	145-148	3	3
7	154-164	10	10
8	176-184	8	8
9	186-194	8	8
10	214-217	3	3
11	239-241	2	2
12	251-259	8	8
13	265-271	6	6
14	278-284	6	6
15	290-292	2	2
16	300-304	4	4
17	304-308	4	4
18	316-322	6	6
19	325-332	7	7
20	339-342	3	3
21	347-351	4	4
22	357-378	9	9

See footnote at end of table.

Table 4.--Thickness of clay and maximum clay-bed thickness--Continued

Layer number	Depth interval (feet)	Clay thickness[1] (feet)	Maximum clay-bed thickness (feet)
23	402-406	4	4
24	412-434	22	22
25	440-450	10	10
26	470-473	3	3
27	474-477	3	3
28	484-493	9	9
29	501-518	17	17
30	554-564	10	10
31	571-574	3	3
32	575-578	3	3
33	581-584	3	3
34	591-599	8	8
35	608-615	7	7
36	617-628	11	11
37	683-686	3	3
38	696-702	6	6
39	708-714	6	6
40	729-732	3	3
41	738-748	10	10
42	751-754	3	3
43	758-762	4	4
44	887-890	3	3

See footnote at end of table.

Table 4.--Thickness of clay and maximum clay-bed thickness--Continued

Layer number	Depth interval (feet)	Clay thickness 1/ (feet)	Maximum clay-bed thickness (feet)
45	976-983	7	7
46	986-992	6	6
47	1,011-1,048	18	18
48	1,068-1,076	8	8
49	1,150-1,190	20	5
50	1,200-1,205	5	5
51	1,220-1,230	10	10
52	1,250-1,290	15	15
53	1,300-1,330	20	20
54	1,340-1,350	8	8
55	1,395-1,400	5	5
56	1,432-1,448	16	16
57	1,457-1,465	8	8
58	1,520-1,527	7	7
59	1,532-1,540	8	8
60	1,560-1,572	12	12
61	1,598-1,608	10	10
62	1,636-1,660	24	24

1/ Clay thickness for layers 1-47 and 48-62 were determined from logs of wells KH 64-33-919 and F-2, respectively.

SELECTED REFERENCES

Allen, D. R., and Mayuga, M. N., 1969, The mechanics of compaction and rebound, Wilmington Oil Field, Long Beach, Calif., USA: Internat. symposium of land subsidence, Tokyo, Japan, 1969, Proc., p. 410-422.

American Oil Company, 1958, Refinery ground subsidence at Texas City: Plant Engineering Depart., Texas City, 58 p.

Corliss, J. B., and Meade, R. H., 1964, Clay minerals from an area of land subsidence in the Houston-Galveston Bay area, Texas: U.S. Geol. Survey Prof. Paper 501-C, p. C79-C81.

Gabrysch, R. K., 1969, Land-surface subsidence in the Houston-Galveston region, Texas: Internat. symposium on land subsidence, Tokyo, Japan, 1969, Proc., p. 43-54.

______1971, Development of ground water in the Houston district, Texas, 1966-69: Texas Water Devel. Board Rept. 152, 24 p.

Gabrysch, R. K., and Bonnet, C. W., 1974a, Land-surface subsidence in the area of Burnett, Scott, and Crystal Bays near Baytown, Texas: U.S. Geol. Survey Water-Resources Inv. 21-74, 48 p.

______1974b, Land-surface subsidence in the Houston-Galveston region, Texas: U.S. Geol. Survey open-file rept., 23 p.

Gabrysch, R. K., McAdoo, G. D., and Bonnet, C. W., 1970, Records of water-level measurements in wells in Galveston County, Texas, 1894-1969: Texas Water Devel. Board Rept. 122, 67 p.

Jorgensen, D. G., 1974, Analog-model studies of ground-water hydrology in the Houston district, Texas: U.S. Geol. Survey open-file rept., 80 p., 40 figs.

Jorgensen, D. G., and Gabrysch, R. K., 1974, Simulated water-level changes resulting from proposed changes in ground-water pumping in the Houston, Texas area: U.S. Geol. Survey open-file rept., 3 p.

Meade, R. H., 1967, Petrology of sediments underlying areas of land subsidence in Central Calif.: U.S. Geol. Survey Prof. Paper 497-C, 83 p.

Miller, R. E., 1961, Compaction of an aquifer system computed from consolidation tests and decline in artesian head: U.S. Geol. Survey Prof. Paper 424-B, p. 54-58.

Naftel, W. L., Vaught, Kenneth, and Fleming, Bobbie, 1975, Records of wells, drillers' logs, water-level measurements, and chemical analyses of ground water in Harris and Galveston Counties, Texas, 1970-74: U.S. Geol. Survey open-file rept., 173 p.

Poland, J. F., 1969, Status of present knowledge and needs for additional research on compaction of aquifer systems: Internat. symposium on land subsidence, Tokyo, Japan, 1969, Proc., p. 11-21.

Poland, J. F., and Davis, G. H., 1969, Land subsidence due to the withdrawal of fluids: Reviews in Engineering Geology II, Geol. Soc. America, Inc., p. 187-269.

Poland, J. F., Lofgren, B. E., and Riley, F. S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal: U.S. Geol. Survey Water-Supply Paper 2025, 9 p.

Pratt, W. E., and Johnson, D. W., 1926, Local subsidence of the Goose Creek Oil Field: The Jour. Geology, v. XXXIV, no. 7, pt. 1, p. 577-590.

Riley, F. S., 1969, Analysis of borehole extensometer data from Central Calif.: Internat. symposium on land subsidence, Tokyo, Japan, 1969, Proc., p. 423-431.

Rose, N. A., 1943, Progress report on the ground-water resources of the Texas City area, Texas: Texas Board of Water Engineers, U.S. Geol. Survey open-file rept., 45 p.

Taylor, D. W., 1948, Fundamentals of soil mechanics: New York, John Wiley and Sons, Inc., 703 p.

Terzaghi, Karl, and Peck, Ralph, 1948, Soil mechanics in engineering practice: New York, John Wiley and Sons, Inc., 566 p.

Winslow, A. G., and Doyel, W. W., 1954, Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region, Texas: Econ. Geol., v. 49, no. 4, p. 413-422.

Winslow, A. G., and Wood, L. A., 1959, Relation of land subsidence to ground-water withdrawals in the upper Gulf Coast region, Texas: Mining Eng., Oct., p. 1030-1034; Am. Inst. Mining, Metall., Petroleum Engineers, Trans., v. 214.

Wolfskill, L. A., 1969, The consolidation characteristics of undisturbed soil samples of deep formations and their application to problems of regional subsidence: Master of Sci. Thesis, Texas A & M Univ., College Station, 70 p.

Wood, L. A., and Gabrysch, R. K., 1965, An analog-model study of ground water in the Houston district, Texas, with a section on design construction, and use of analog models, by E. P. Patten, Jr.: Texas Water Commission Bull. 6508, 103 p.